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Hydro Artificial Muscle Exo-Musculature

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Hydro Artificial Muscle Exo-Musculature

A Major Qualifying Project Report:

submitted to the Faculty of

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

by

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Professor Marko Popovic, Primary Adviser
Abstract

The Exo-Musculature project is a novel hydraulically-actuated elastic muscle, which is inspired by the capabilities of a biological muscle. The design has certain advantages over natural muscles, such as being able to maintain a position without expending energy. This design uses an elastic element to apply tensile force, which is released when hydraulic pressure is applied. This gives the muscle the unique characteristic of storing elastic energy when pressurized and releasing it to contract. Other artificial muscles, such as the McKibben, are similar to ours in the respect that they are fluid-actuated and can be locked in place, but the McKibben requires suction or pressure to expand and contract. Additionally, our muscle is limited to expansion in only one dimension, which offers a higher energy density. It is much more compliant than traditional hydraulic cylinders, making it better suited for use in human rehabilitation and augmentation. Finally, our prototype is constructed using common materials, making it an extremely low cost solution for both medical and robotic applications.
Acknowledgements

We would like to thank our advisor for this project, Professor Marko Popovic, for all that he has done to help us and guide us and see this project through.

We would also like to thank our other advisor for this project, Professor Cagdas Onal, for all the advice and guidance he has given to us over the course of this MQP, as well.

Lastly, we would like to thank Physics Department Lab Coordinator, Fred Hutson, for helping us out and allowing us to use physics lab rooms and equipment for experimentation of our muscles.
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1 Introduction

1.1 Motivation

A major development in today’s robotics industry is soft robotics. Traditional robotic systems typically comprise of rigid structures that operate in pre-established movement patterns for industrial purposes. The shift to soft robotics aims to increase the compatibility of robotic systems with the human body by mimicking biological structures. This bio-inspiration allows for soft robotic actuators to move in many degrees of freedom and vary the level of force output, similar to human skeletal muscles. The recent surge in soft robotic technology is due to the advances in other technologies like computing power, communication technologies, sensors, and electronics integration (Albu-Schaffer, et al., 2008).

The motivation for the Exo-Musculature MQP is to implement a soft robotic actuation system to assist in the movement of the human body. There is a wide array of muscular degenerative disorders that affect millions of people worldwide every year. The most common type of muscular dystrophy, Duchenne muscular dystrophy, occurs in 1 of every 3300 male births (The Internet Stroke Center, n.d.). In addition, stroke, the leading cause of serious, long term disability in the United States, affects 795,000 people each year (Virtual Medical Center, 2014). Finally, the elderly population (65 and older) in the United States was 40.3 million in 2010, which was 13% of the total population. This number continues to grow and the elderly are predicted to comprise of 20% of the population of the United States by 2050 (Department of Health and Human Services, n.d.). The constant increase in the size of the elderly population creates a large market for human-compliant rehabilitation devices that utilize soft robotics. These instances, as well as a number of other diseases and disabilities can be addressed with the use of a soft robotic actuation system for rehabilitation and strength augmentation purposes.

The high demand of assistive technology that complies with the human body drives the development of soft robotics. Many individuals cannot complete the simplest of tasks which require precise movement of arms, legs, and all other skeletal muscle extremities. A hydraulically actuated exo-musculature can be used to promote muscular rehabilitation, while allowing the user to wear the device comfortably with the body’s natural movement in mind. A fully functional and comprehensive exo-musculature has the potential to provide assistive movement for an entire human body by replacing the often cumbersome and limiting traditional robotic system.

1.2 Background

1.2.1 Biologically Inspired Design

The Exo-Musculature MQP is based upon biologically inspired, hydraulically actuated artificial muscles. Specifically, the hydraulic muscles aim to imitate three of the most prominent bicep muscles, in the short and long heads of the biceps brachii and the brachioradialis muscles. However, the hydraulic muscle only replicates the use of the
biceps muscles in function, not the process in which the function is completed. In fact, the hydraulic muscle works in the opposite way as biological muscles. When a biological muscle pulls, or actuates, it contracts and expands radially. In contrast, when the artificial muscle actuates, it contracts and decreases in size longitudinally, using elastic potential energy to provide the motion.

While the hydraulic muscle does not entirely imitate biological bicep muscles, the inspiration and function are still biologically dependent. In recent years a major trend in science explores deriving solutions to mechanical problems from biological systems, especially as our understanding of biological phenomenon becomes more detailed. The validation for this concept is that biological systems have been continuously improving themselves to complete a specific task for millions of years through the process of evolution. Through generations of improvements, organisms have been forced to adapt to most effectively and efficiently expend energy in order to continue to survive. Many of these tasks, environments, and constraints are similar to those relevant to engineering design (Chakrabarti & Shu, 2010).

In the coming years biology will continue to provide engineering solutions and answers to engineering problems. In the past, we were able to observe biological systems from an external viewpoint and learn from straightforward and broad concepts like how birds create lift or how fish use their fins to propel themselves in water. However, as technology improves and our understanding of natural systems becomes more complete, even at a molecular level, biological design will provide practical solutions for engineering applications.

1.2.2 Benchmark Products

The hydraulic artificial muscle combines a novel method of actuation and design to create a product that has not yet been seen on the commercial market or in the academic realm. However, there are several US patents that deliver similar ideas, which can be compared to the hydraulic muscle and used as benchmarks for our own product. In addition, a significant invention that has many similarities and delivers relevant contrasts is the McKibben muscle.

A major influence on the design of the hydraulic artificial muscle is the McKibben artificial pneumatic muscle (Chou & Hannaford, 1992). This muscle has the same function as the hydraulic artificial muscle, a bio-inspired actuator, but the similarities end there. The most prevalent difference seen in the McKibben muscle is that it uses pneumatics, rather than hydraulics as its working fluid. Air is compressible whereas liquid is incompressible providing the hydraulic muscle with better response times and a higher energy density. Another difference between the two products is how the muscle acts when their respective working fluid is used to pressurize the muscle. The hydraulic muscle uses elastic potential energy to provide the pulling motion where the McKibben muscle uses air pressure to contract, therefore providing the pulling motion. While these two muscles work in opposite ways, it is the McKibben that more closely imitates a
biological muscle, but the hydraulic muscle uses stored elastic potential to create a more efficient and responsive actuator.

![Figure 1: McKibben Pneumatic Artificial Muscle](image)

Several US patents of garden hose systems (Degen, Gregorian, & SIBER, 2007; Ragner & deRochemont, 2001; Berardi, 2011) have provided inspiration for the hydraulic artificial muscle. These systems have two openings on either end, compared to only one on the hydraulic muscle where the force can be accumulated when additional pressure is added to the system. The hydraulic muscle is designed for controlled force release of an incompressible fluid using sensory input on muscle length and force. Muscle length is determined by measuring the electrical resistance of fluid across the muscle and muscle force is determined by attaching strain gauges at the muscle-load attachment points.

The specific commercial product that these patents relate to is the X-Hose (XHOSE - the Original Kink Free Lightweight Expandable Garden Hose, n.d.). This product acts almost entirely the same as the hydraulic muscle in that it comprises of an elastic inner material surrounded by an inelastic material that limits the expansion of the elastic material in the radial direction, but not the longitudinal direction. Also the X-Hose retracts to its original size when the pressure is released.

![Figure 2: X-Hose Design and Function](image)

Further patents (Degen, Gregorian, & SIBER, 2007; Ragner, 2003; Ragner & deRochemont, 2001) are systems with corrugated walls that expand under fluid pressure. The hydraulic muscle utilizes smooth elastic walls for its tubing, rather than the corrugated elastic material. Therefore, the hydraulic muscle is more simply manufactured and inexpensive. Additional similarities include the non-stretchable sleeve
made of a soft, inelastic material, such as polyester, to limit radial expansion while promoting lengthwise expansion when pressurized.

1.2.3 Integration of Hydraulic Artificial Muscles

In order to demonstrate how the hydraulic artificial muscle would function in a real-world application, three muscles were attached to the arm of a model skeleton. These muscles were positioned in relative accordance with the actual attachment points of biological muscles, specifically the long and short heads of the biceps brachii and the brachioradialis. By positioning the muscles in this fashion, a proper demonstration could be conducted that would allow any observer to immediately recognize the function of the muscles and relate them to a biological system. Figure 3 illustrates the arrangement of the hydraulic artificial muscles to mimic the configurations of actual elbow flexor muscles.

![Figure 3: Integration of Hydraulic Artificial Muscles on Skeleton](image)

The hydraulic artificial muscles could not be directly connected to the bone of the skeletal model so a custom, latticed device was created. The device was attached to both the upper arm and forearm of the skeleton and allowed for the position of the muscle attachment points to be varied up and down the arm because of the lattice structure. Further development of exo-musculature integration will allow for a complete skeletal muscle model that can actuate many degrees of freedom. Figure 4, for example, explores a configuration where a muscle is attached as a shoulder flexor so that the model can actuate with two degrees of freedom.
1.2.4 Biomechanics of Arm and Bicep Muscles

Our model aims to demonstrate how the hydraulic artificial muscles can function in real world applications by replicating the capabilities of a biological set of elbow flexor muscles. For practical and manufacturability purposes, we replicated the two heads of the biceps brachii muscles and the brachioradialis. These muscles represent the two most influential forces pulling the forearm up and have the same function as the elastic tubes which contract due to elastic potential energy.

We analyzed the muscle forces of an arm at 30 degrees of flexion from the vertical. For this initial case, the arm is simplified into a system with almost no complexity. All of the agonist muscles acting on the arm during flexion are simplified into a single force along the bicep. To keep this analysis simple, the friction of the elbow joint has been ignored. A free body diagram and table of variables for this case are shown Appendix A.
Through the law of sines and the law of cosines we were able to solve for the muscle angle. With these values computed, we could formulate the remaining 3 equilibrium equations; the sum of moments, sum of forces in the x-direction, and the sum of forces in the y-direction. By solving those three equations, we are able to determine the muscle force and joint force of this system by substituting in known values. The muscle force is obtained as shown below.

\[
F_{\text{muscle}} = \frac{(L_{\text{CoM}} \ast W_{\text{arm}}) \cos \beta}{AP_1 \sin(\theta)}
\]  

(1)

With these values computed, we were then able to calculate the moment arm that the muscle forces are applied along using the equation shown below.

\[
\text{Moment Arm} = AP_1 \sin \theta
\]  

(2)

Using the governing equations above, we are able to get a set of baseline values for forces and moments acting on the arm. We can then compare these values to experimental results produced by our prototype to see how the mathematical model and physical model differ. We know that results will not exactly match because of the many assumptions made in the mathematical model, such as the frictionless system and the collection of the muscle's forces into one bicep muscle force. Further mathematical models can be formulated which include independent forces from each muscle, friction, weight of an object lifted, and co-contraction muscles, like the triceps. Our physical model can be considered modular because the muscles can be attached at different points along the lattice structured integration device. Because of this characteristic, the forces and moments present in the model can be calculated for a variation of muscle configurations.

1.2.5 Exo-Musculature

This MQP began as a continuation of MQPs from previous years. The purpose of our MQP was to design a soft robotics hydraulically-actuated artificial muscle. Our design had to be compliant enough to be worn on a human body. Our advisor, Professor Marko Popovic, used the term, “exo-musculature” to describe his research into more biologically-inspired alternatives to exo-skeletons and prosthetics which are currently being used.

Professor Popovic first introduced the word, “Exo-musculature” to describe a compliant, wearable garment that used cables to actuate movement. The benefit of this was that it was much more compatible with human movement than exo-skeletons or metal braces. It contained no joints or rigid elements, and it had several cables to actuate several degrees of freedom. Without these rigid elements, the Exo-musculature garment is able to better conform to an individual’s body shape and movement. Since then,
Professor Popovic has hosted several MQPs looking to advance his Exo-musculature design. The two previous projects were concerned with One-To-Many systems.

### 1.2.6 One-To-Many System

The problem with having a soft robotics Exo-musculature system is that it has to be able to replicate every degree of freedom the human body has. There is on the order of one thousand different individual degrees of freedom. It would be cumbersome and impractical to have a single electric motor control a single degree of freedom, the way robotics are currently used now. In order to solve this problem, an MQP team from two years ago built a proof of concept of a One-To-Many (OTM) system. This system was designed to have one motor control multiple degrees of freedom.

That was achieved by having an electric motor store energy on springs, and then control the springs in order to actuate the degrees of freedom. In that manner, a single electric motor could be used to actuate multiple, and potentially hundreds of, degrees of freedom. The next year, the MQP was used to design a rotary OTM system. A single motor would charge multiple torsion springs, each with their individual way of being actuated. Again, one motor could actuate several degrees of freedom.

That brings us to this year’s MQP. Professor Popovic was interested in the high energy density of fluids, and he wanted us to continue the previous years’ projects and construct a hydraulic OTM system. We were at will to decide both the scope of the project and the design of the system.
2 Proposed Design

2.1 Goals

During one of our first meetings, we together decided on the scope of the project and goals that our design needed to meet. We wanted our design to, like the previous designs, have some manner of storing energy in order to release the energy in a controlled fashion. That way, we could have one hydraulic pump running continuously, similarly to how the previous OTM systems could have an electric motor running continuously. We also decided that our design had to be a closed system; all the water used had to be constantly recirculated throughout the system.

Because this system was supposed to be worn on a body as an Exo-musculature system, we needed to make sure it was portable and light. We set the parameters that it had to be no larger than a child’s backpack and no heavier than 45 Newtons. Again, because this needed to be worn by people and might have to be used for long hours, we set the parameter that our project had to be able to run nonstop for at least two hours. We wanted to be able to show the ability of this system to be used in real-world environments. We wanted our system to be able to lift at least a gallon of milk. This meant that we had to be able to generate 100 Newtons of force.

We also had three requirements in relation to our system being an OTM system. Firstly, it must be modular. It has to be able to have more actuators connected or removed as necessary. Related to that, we also wanted to be able to control each actuator individually. We needed to have the ability to control different actuators at different times, while the pump was running in order to demonstrate the OTM nature of the system. Lastly, we decided that the system needs to be able to control at least two degrees of freedom at once. The purpose of an OTM system is to use one motor or pump to control multiple degrees of freedom. We wanted to connect at least two actuators, controlling two separate degrees of freedom to our system.

2.2 Design

We were looking at several ways to store energy and actuate movement with a hydraulic system. For storing energy, we looked at different designs of hydraulic accumulators. We wanted a way of slowly storing high pressures and volumes of water in an accumulator, and then being able to release it at once into an actuator. We were looking at storing the water in an elastic container, which would help propel the fluid out when there was a high difference in pressure. For the actuator, we wanted what would basically be a compliant, soft robotics alternative to hydraulic pistons and cylinders.

It was when we combined the idea of the elastic accumulator with the actuator that we stumbled onto our main design concept. We figured out that if we used the contracting movement of the elastic as the muscle force, creating a tensile force rather than a compressive force, it could act similarly to an actual biological muscle. At that
point, we needed to figure out a way to restrain the elastic so that it can only expand and contract in one dimension. If we were to connect an elastic bladder like it was human bicep, when we filled it with fluid, it would obviously expand in all directions. We figured that if we used a long elastic tube instead of a bladder, surrounded by a wrinkled, inelastic fabric material, the inelastic material would prevent the elastic tube from expanding radially. The inelastic tube would, under higher pressure from the fluid inside of it, have to expand longitudinally. As the elastic tube expands along its long axis, the wrinkled inelastic material would begin to unwrinkle. It would only stop once the inelastic material has become completely unwrinkled and has extended to its full length. Figure 6 demonstrates the relaxed position of the muscle, while Figure 7 shows the muscle fully extended.

Once we had conceived of this original design, we focused more on it than on the OTM system. While our current prototype does meet the three goals set down for an OTM system, it is still not one. This is because our design, while it does use elastic to store potential energy, the pump still directly actuates the muscles. There is no energy-storing mechanism between the artificial muscle and the pump. Although, keep in mind that the muscles can still all contract individually; all we needed to do was find a way to release the pressure inside the muscle whenever we wanted. While it contracts independently of the pump, it still directly requires the pump to extend the muscle.
3 Methods

3.1 First Prototype

Once we had our design, we began constructing our first prototype. This was built with materials we could buy easily and cheaply. We wanted to test out a few designs, including a muscle that had latex surgical tubing as its elastic element and a muscle that used an elongated balloon as its elastic tubing. The first prototype we built was using the latex tubing, and it functioned very well. Figures 8 and 9 depict this first prototype in its relaxed state and in its extended state.
Our second design failed before we could ever complete any tests. A balloon did not have the same structural integrity as the surgical tubing. It did not expand evenly, and it was too weak to be able to lift almost anything when it contracted.

3.1.1 Elastic Muscle
Our elastic muscle was constructed using latex surgical tube that cost $16.31 for 10 feet. The seven inches we used, then, comes out to less than $1. We sealed off one end by melting a small bit of latex at that end. On the other end, we used a plastic connector that we found in the lab to connect the muscle to a polyethylene tube. We used a small piece of polyester cloth that we bought for $6 per square yard as the inelastic outer wrap. Of that square yard, we cut a piece about 15 inches by 3 inches. That comes out to about $0.20 for the fabric for that single muscle. We secured the ends of the fabric to the ends of the latex tube by using small pipe clamps on each end. Each pipe clamp cost $0.78. In Section 3.2, we go into detail about the physical properties used in the muscle prototypes.

3.1.2 Pumping Unit
For the pumping unit, we simply used a bicycle pump. We had a sealed-off reservoir into which we would pump air using the bicycle pump. As the pressure increased, it forced water into the muscle. We released the pressure in the muscle simply by taking the bicycle pump nozzle out of the reservoir.

3.1.3 Reservoir
As for the reservoir, we used an empty soda bottle, filled half way with water. This was a good idea, we decided, because soda bottles are made to seal tight despite a high gauge pressure. We connected the muscle to the reservoir using polyethylene tubing which we submerged in the water in the reservoir. We used about four feet of polyethylene tubing at $7.34 for 25 feet. That portion of the polyethylene tube would then cost about $1.15. The nozzle of the bicycle pump was secured in the top of the soda bottle. When the bicycle pump was pumped, air was forced into the top, increasing the pressure, and forcing water through the polyethylene tube and into the muscle, extending it.

All in all, taking into account how much we used of each item, the cost of this single prototype muscle was somewhere between $3.50 and $4.00. In Figures 8 and 9, you can see the setup of the first prototype, complete with all the materials which were just described, as it goes from a relaxed state to an extended state. These pictures were taken during out first real test with our artificial muscle design. Complete experimental results can be found in Appendix B. We found that this muscle could exert a maximum force of about five pounds. It is safe to say that our first prototype was largely a success. We were able to build a very successful proof of concept using materials that cost less than $5 altogether.
3.1.4 Improvements Needed for Next Generation

The biggest change between our first prototype and our next model would have to be that our next model needed a fully-functioning hydraulic system. That is, we needed to construct a system that had a pump and reservoir and a specific layout of the plumbing; we also needed electric valves that could be controlled with a microprocessor; and lastly, we needed multiple muscles to be able to be functioning at the same time. Our first prototype demonstrated the success of the physical capabilities of the muscle design. At this point, we needed to design an entire controlled, hydraulic system to actuate the different muscles.

We also needed some improvements on the muscle. The stitching which held the inelastic material together around the latex tube was subpar workmanship. None of us knew how to sew very well. This allowed the latex to bulge in certain places, and the latex did not expand as evenly as it potentially could. In order to improve this aspect, we needed to find and utilize a sewing machine on the next generation’s polyester coat.

Overall, the muscle, although it functioned very well, was somewhat leaky. We needed to improve the workmanship and quality of the next muscles we built. We knew at this point what needed to go into the muscles, so we could then construct them much more carefully and robustly.

3.2 Second Prototype

The second prototype was designed as a continuation of the first prototype. This prototype also constitutes our final design and proof of original invention. The process of designing followed the standard procedures described below:

Initially, a theoretical model was formulated, as iteration to the model used previously. This new model featured changes that arose from the specific limitations and requirements that had to be met. Specifically, the second model takes into account kinematics of the arm and improves on the biocompatibility of the design. This is achieved by including precise insertion points of the long and short biceps for torque calculations. Additionally, the model was altered to include three (3) hydro artificial muscles (HAMs) operating simultaneously and in parallel.

Following, a non-working model of the prototype was made to test the size and weight of the HAM. This non-working model allowed us to experiment with the elastomer and test the integration onto a regular sized skeleton.

Next, all the parts necessary for the assembly of the system were acquired and tested under maximum theoretical load and through multiple cycles of operations. The particular parts that we were interested in testing for durability were the pump, the solenoid valves and the HAM. These components were experimentally proven to run continuously and faultlessly for up to 6 hours.
<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHURflo pump</td>
<td>1</td>
<td>Pumping</td>
</tr>
<tr>
<td>1/2&quot; 12V plastic solenoid valve</td>
<td>6</td>
<td>Flow Control</td>
</tr>
<tr>
<td>1/2&quot; brass 75 PSI release valve</td>
<td>1</td>
<td>Safety/Discharge</td>
</tr>
<tr>
<td>Arduino Uno control</td>
<td>1</td>
<td>Valve Control</td>
</tr>
<tr>
<td>3/8&quot; x 25' polyethylene tubing</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1/2&quot; x 25' vinyl tubing</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>3/8&quot; by 1/2&quot; QC adapter</td>
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<tr>
<td>1/2&quot; QC by 1/2&quot; adapter</td>
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<td></td>
</tr>
<tr>
<td>1/2&quot; by 3/4&quot; brass coupling</td>
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<td></td>
</tr>
<tr>
<td>3/4&quot; 5-way brass valve</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>3/4&quot; by 1/2&quot; brass swivel coupling</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>1/2&quot; black steel tee</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>1/2&quot; by 3/8&quot; QC adapter</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>1/2&quot; brass coupling</td>
<td>5</td>
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<tr>
<td>3/8&quot; tube adapter</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>electrical wiring (50')</td>
<td>1</td>
<td>Wiring</td>
</tr>
<tr>
<td>3/8&quot; latex tubing (10')</td>
<td>1</td>
<td>Muscle</td>
</tr>
<tr>
<td>Polyester Fabric (1 yard)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Electrical components</td>
<td></td>
<td>Valve Control</td>
</tr>
</tbody>
</table>

Table 1: Components List

Observing the Table 1 above, one should note that the essential components are presented in bold. These are the pump, the solenoid valves, the pressure release valve, and the Arduino Uno control. The remaining components comprise the plumbing and electrical setup and include tubing, adaptors, flow splitting T’s, and various electrical components.

![Figure 10: Schematic of the System](image)
This plumbing setup utilizes a positive displacement diaphragm pump that operates continuously. The pump is rated at 150 PSI with a measured maximum of 145 PSI. The operational pressure was estimated to be approximately 80 PSI. It can output 1.4 gallons per minute (GPM) for open-flow; however, the flow rate was downscaled for safety purposes, outputting constant 0.7 GPM flow. The working fluid used for the prototype was tap water at ambient temperature.

The water was drawn from a 5 gallon reservoir and pumped through the pressure release valve. The pressure release valve was rated at 75 PSI and served as a discharge and safety mechanism. Following, the fluid reaches the solenoid valves that are arranged in a T formation.

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. The pressure release from the muscle makes it contract robustly providing a pulling force of 35 Newtons for each muscle.

3.2.1 Elastic Muscle

As seen in Section 2.2, the elastic muscle used for the second prototype was the final design of the actuator. The design features a latex surgical tube on the inside and a polyester fabric on the outside. The muscle has a brass plug on the proximal end and a plastic adapter on the other end. The plug and the adapter are concentric and tightly installed. The fabric is attached to the tube with common metal hose clamps.

![Diagram of elastic muscle with components labeled](image)

Figure 11: Contracted elastic muscle with components labeled
More specifically, the adapter used is a 3/8” male to male (nipple) PVC connector. It is relatively inexpensive and durable. Additionally, it is easily modifiable for the purpose of adding sensors to it. The latex tubing used is 7” in length and has an inner diameter of 3/8”. The specific type of latex used is natural rubber latex that meets the FDA safety grade requirements and has the following properties:
This type of material was chosen for its exceptional resistance to wear and tear, high tensile strength, resilience, and elongation. The main disadvantage is the susceptibility to corrosion due to heat, sunlight, and oxygen. However, it can be regarded negligible as the tubing is not fully exposed. The operational temperature of latex is between -55 and 82 degrees Celsius.

The outer sleeve is made out of polyester and has an approximate length of 16in. It is ideal for our application as it is rigid, tough and has low absorption of moisture. Additionally, it has a high flexural linear strength.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile</td>
<td>3500 PSI</td>
</tr>
<tr>
<td>Ultimate Elongation</td>
<td>750%</td>
</tr>
<tr>
<td>100% Modulus</td>
<td>120 PSI</td>
</tr>
<tr>
<td>500% Modulus</td>
<td>300 PSI</td>
</tr>
<tr>
<td>Tensile Set/ Memory</td>
<td>2%</td>
</tr>
<tr>
<td>Hardness</td>
<td>35 ± 5</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>.923 g/cc</td>
</tr>
</tbody>
</table>

Table 2: Mechanical Properties of Natural Rubber Latex

<table>
<thead>
<tr>
<th>Property</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic Modulus</td>
<td>2580 MPa</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>60 MPa</td>
</tr>
<tr>
<td>Elongation</td>
<td>300%</td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>115 MPa</td>
</tr>
<tr>
<td>Hardness</td>
<td>68</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>1.3 g/cc</td>
</tr>
</tbody>
</table>

Table 3: Mechanical Properties of Polyester

---

1 Natural Rubber Latex Tubing Data Sheet K-100, Kent Elastomer Products, INC.

2 MatWeb
3.2.3 Pump
The pump used for the system is SHURflo 8035-963-239 12VDC diaphragm manual demand pump. It is a positive displacement, 3-chamber diaphragm pump that utilizes maximum discharge pressures to deliver high flow rates. The check valve is 2-way operational and prevents reverse flow while providing 6ft head of forward flow. The specifications are listed in Table 4:

Latex
• High tensile strength
• Resilience
• Elongation
• High linear elasticity

Polyester
• Strong
• Light weight
• Low moisture absorption
• Sun resistant

Figure 14: Advantageous Properties of Latex and Polyester
The temperature rise of the pump is controlled by a thermal protector with a trip point of 205 degrees Fahrenheit. The following graph shows the temperature rise under a continuous run cycle. The test was performed with an ambient temperature of 75 F in still air. The temperature rise graph of the pump can be found in Appendix D.

The typical performance of the pump for 6 operational pressures is controlled by the manual demand switch and presented in Table 5:

<table>
<thead>
<tr>
<th>Model Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 8035-963-239</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pump Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Positive Displacement 3 Chamber Diaphragm Pump</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Check Valve</th>
</tr>
</thead>
<tbody>
<tr>
<td>• (2-way Op.) Prevents Reverse Flow &amp; 6 Ft. Head Forward Flow</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cam</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 3.0 Degree</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Permanent Magner, P/N 11-223-00, Thermally Protected</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 115 VAC Nominal</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pressure Switch</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Adjustable Shut-Off (Range 140-160 PSI), Factory Set @ 150 PSI, Turn On 115 PSI</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Liquid Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 180 Degrees Fahrenheit (82 Degrees Centigrade) Max.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Prime</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Self-Priming Up to 6 Ft. Vertical, Max. Inlet Pressure 30 PSI</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ports</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 3/8” - 18 NPT Female</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material of Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Nylon (Plastics), EPDM (Valves), Santoprene (Diaphragm), Zinc Plated Steel (Fasteners)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Net Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 5.94 Lbs (2.7 Kg)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Duty Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Intermittent</td>
</tr>
</tbody>
</table>

Table 4: Pump Specifications
As mentioned above, the pump was running at a 0.7 GPM discharge rate, which according to the graph above required a pressure of 120 PSI. The discharge rate was chosen as such for safety purposes, as well as to make sure that the muscles receive a pressure of 30 PSI after head loses. The entire specifications of the pump, including a schematic of the pump, can be found in Appendix D.

### 3.2.4 Valves

The solenoid valves used for the system were plastic water solenoid valves 12V ½” Nominal. The resting position is closed. The valve requires 12VDC on both terminals to open and allow flow in one direction. The gasket arrangement inside of the valve requires a minimum pressure of 3 PSI to operate. This is because they are one-way valves. The 3 PSI of pressure keeps the valve closed. When the 12 V is sent to the solenoid, it forces the valve open against the flow.

![Figure 15: Images of the Solenoid Valves](image)

The valve was tested at various DC voltages and it would operate with voltages as low as 6V. The current draw table for that configuration is presented in Table 6:
Table 6: Current Draw for Various Voltages

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>6V</td>
<td>160 mA</td>
</tr>
<tr>
<td>7V</td>
<td>190 mA</td>
</tr>
<tr>
<td>8V</td>
<td>220 mA</td>
</tr>
<tr>
<td>9V</td>
<td>240 mA</td>
</tr>
<tr>
<td>10V</td>
<td>270 mA</td>
</tr>
<tr>
<td>11V</td>
<td>300 mA</td>
</tr>
<tr>
<td>12V</td>
<td>320 mA</td>
</tr>
</tbody>
</table>

The valves were proven to work flawlessly with fairly acceptable response times. It should be noted that the valve terminals can get hot under continuous operation. These particular valves were chosen because they were inexpensively and made from durable materials. The specifications for the valves are located in Appendix D. You can see a photograph of the full hydraulic system, also located in Appendix D.

3.2.5 Muscle Attachment to the Skeleton

The hydraulic artificial muscles could not be directly connected to the bone of the skeletal model so a custom, latticed device was created. The device was attached to both the upper arm and forearm of the skeleton and allowed for the position of the muscle attachment points to be varied up and down the arm because of the lattice structure. Attachment of the muscles to lattice device itself was accomplished using rectangular sheet metal cutouts. The thin sheet metal was cut into approximately 1 inch by 3 inch pieces and then bent a third of the way down at a 90 degree angle. On one third of the piece we drilled a hole so that the cutout could be aligned, concentrically, between the adapters of the elastic muscle and polyurethane tubing for a sturdy and permanent attachment. The other half of the cutout was bent to look like a hook so that it could be fastened around any segment of lattice structure that is desired. Finally, because of the malleability of the sheet metal, we were able to adjust the bend angle so that the open end of the muscle and adapters stayed parallel to maintain the structural integrity of the elastic. This design allowed for easy detachment and attachment at both ends so the muscles could be arranged in a variety of configurations. Figure 15 shows how the muscle was attached to the lattice.
Further development of exo-musculature integration will allow for a complete skeletal muscle model that can actuate many degrees of freedom. Appendix C, for example, explores a configuration where a muscle is attached as a shoulder flexor so that the model can actuate with two degrees of freedom.

3.2.6 Sensors

We wanted to have a way of sensing the position of limb which was using the muscles. Since we had decided to attach the muscles to function as bicep muscles, we wanted to know the angle of the fore arm with respect to the upper arm. We decided early on against a potentiometer, because of our goal to make our design modular. We wanted everything integrated into each muscle that would be necessary for it to function. So, we had to figure out a way of measuring the length of the muscle. Our decision was to see if we could measure the conductivity of the water inside the muscle.

We performed an experiment, the results of which are found in Appendix B, with simply a basin of water, a power source, electric probes, and a known resistor. The point of the experiment was to see how well we could determine the distance between two probes submerged in water, based on the resistance we measured. We connected the power supply to a voltage divider, with one “resistor” being the water between the probes, and the second resistor was a 100 kΩ resistor. We then measured the voltage drop across the 100 kΩ resistor. From that, we calculated the resistance of the water. We redid the experiment several times at different distance, until we had enough data points to plot. You can see this set up in Appendix E. The results show a highly linear relationship between distance and resistance.

In order to make this into a usable analog signal for the Arduino (which we will discuss later on), we needed to change the resistance into a signal that varied linearly between 0 and 5 Volts. We could use a voltage divider, like we did with the water experiment, to convert the resistance into a proportional voltage. But, we still needed a
way to make sure that voltage got converted into another voltage that ranged from 0 Volts when the muscle was full contracted and 5 Volts when the muscle was fully extended. A differential amplifier circuit, which is a specific configuration of resistors and an op amp, is designed specifically for that purpose.

What we needed to do was thoroughly test the muscle’s resistance when the pump was on and controlling the muscle’s extension and contraction. Once we had the minimum resistance, we would have had the voltage divider hooked up with the muscle’s minimum resistance. That would cause the output of the voltage divider to be half of whatever the source voltage was. We would have that voltage feed into the positive input for the op amp, while the negative input would permanently be at half the source voltage. The difference between the two voltages would be at, or close to, 0 Volts when the muscle was at its minimum position. Then, when it was at its maximum position, we would measure the resistance again, calculate the output from the voltage divider, and subtract half the source voltage from that to determine the differential voltage. Lastly, we could divide 5 V by that differential voltage to find the ratio of the resistors we would need to have the differential op amp run well. For a visual representation of the circuit, as well as the mathematics required, see Appendix E. It should be noted that it is imperative to take into account the Thévenin’s equivalent resistances of both the voltage dividers when trying to find the proper resistances.

That was a solid plan. The problem was that when we tested the resistance of the muscle with the pump running, we got numbers we were not expecting. You can see the full data from that experiment in Appendix B. You can see from the first graph from that experiment that the resistance does not grow linearly until the muscle has extended to about nine inches. What we had not taken into account was the fact that the latex tube would expand radially a little bit. More about this experiment will be discussed at length in Sections 4.5 and 5.1.5.

We were able to successful build a circuit that accurately calculated the distance between nine inches and its maximum extension. However, because of the bizarre behavior of the resistance between seven inches and nine inches, that was the best we could do. It was not until halfway through D Term that we were able to construct a fully functioning hydraulic system, so it was not until then that we were able to test the muscle resistance. With so little time left, we were not able to get the length sensors working in time. If we could continue to work on it, we might be able to design an accurate way of determining the length of the muscle using the resistivity of the water.

3.2.7 Controls Unit

Our system is controlled by an Arduino Uno microprocessing board, based on the ATmega 328 (Arduino, 2014). The Arduino communicates with a computer via a USB cable. We programmed the Arduino to control the solenoid valves from instructions from the computer. The Arduino listens to the keys pressed, and it opens or closes the valves
depending on which key was pressed. Appendix F has all three of the programs we wrote to interact with the Arduino and control the valves.

We downloaded the freeware, PuTTY, to interface with the Arduino. PuTTY prints and sends messages to the USB of our choosing. We used it specifically to provide a very bare, basic graphical user interface for someone controlling the valves. It told us when certain valves were open and when they were closed, depending on which program we were running. Figure 16 shows the initial screen from the open_close_valve_3.ino program, and Figure 17 shows what the GUI looks like after a few commands have been sent.

![Figure 16: Initial Screen for open_valve_close_3.ino](image1)

![Figure 17: Initial Screen for open_valve_close_3.ino Output after a Few Commands from User](image2)
As for the actual physical controlling of the valves, we used transistors to provide a 12 Volt supply to the solenoids. Specifically, we used six NPN bipolar junction transistors (BJTs). Each of their base pins was connected to each one of the six digital I/O ports between 8 and 13 on the Arduino. The Arduino would send a “high” 5 Volt signal to the base of the transistor, which would allow for the 12 Volts to be sent to that specific valve. The positive 12 V terminal fed into the valve, which, in turn, fed into the collector pin of the BJT. The emitter pin was grounded. This is a fairly simple circuit, but there is a visual representation of it in Appendix E.

![Figure 19: Photograph of Arduino, Controller Setup](image)

The photograph in Figure 18 shows this set up with a breadboard and LEDs to show which valves are open. The black, square objects right next to the LEDs are the BJTs. You can see the wires going from the BJTs to the Arduino’s I/O pins. The three yellow wires at the right are connected to the 12 V power supply. The top is the positive terminal, and the bottom two wires are the ground and the negative terminal, respectively. The positive terminal is connected to the red rails of the breadboard, while both the ground and the negative terminal are connected to the blue rails of the breadboard. The orange wires at the bottom of the photograph are going to the valves. You can see that for each pair of orange wires, one goes to a BJT and the other goes to the positive (red) rail on the bread board.
4 Experiments

Throughout the development of the Exo-Musculature project, several experiments were performed in order to test the capabilities of the hydraulic muscle and to develop a sensor to detect muscle expansion. Since there are three main variables related to muscle actuation (input pressure, length of expansion, and force exerted), two different types of experiments were conducted on the muscle: constant length and constant force. For the first prototype, an experiment relating expansion to pressure for several constant forces was performed. For the second and final prototype, separate experiments were carried out for constant length and constant force cases. In addition, an experiment was carried out to assess the feasibility of a length sensor based on the electrical resistance of the water within the muscle. One final experiment was performed to test this resistance-based length sensor on the actual muscle prototype. All the results of the experiments can be found in Appendix B.

4.1 First Prototype: Relationship between Length, Internal Pressure, and Force

To test the first prototype, various weights were affixed to one end of the muscle to apply a constant force. The internal pressure of the muscle was raised incrementally and the change in length recorded. One end of the muscle is affixed to a clamp at one end of the table. A section of tubing supplies this end of the muscle with water from a special apparatus designed to convert power from the pneumatic bicycle pump into hydraulic power for the muscle. Due to budget restrictions, a pressure interface device was fashioned from a plastic soda bottle. The hydraulic tube from the muscle runs through the cap, via a double-barbed pipe fitting sealed with a gasket and nut. A bicycle pump pressurizes the bottle via another hole in the cap. This pushes the water in the bottle up the hydraulic tube. The bicycle pump also provides a gauge to measure to pressure of the system. Because the scope of this experiment only covers the system when it is at rest, measurements are only taken when the system is in equilibrium and the pressure at the pump will be the same as the pressure within the muscle. The other end of the muscle is attached to a string that runs over the far end of the table and is attached to a lightweight bag where various weights are placed. There is a smooth cylinder under the string at the corner of the table to act as a makeshift pulley and reduce friction.

To perform this experiment, a certain amount of weight is placed in the holding bag and the system is pressurized to a specific level. The length of the muscle is recorded and the pressure and/or weight are changed for the next reading. Figure 20 shows a photograph of the setup. Section 5.1.1 has the results of this experiment.
4.2 Relationship between Electrical Resistivity of Water and Distance

Any method of controlling the muscle will require some suite of sensors and feedback devices. If sensors are integrated into the muscle architecture, integrating the muscle into future designs will be much more simple and modular. Measuring the change in electrical resistance between either ends of the muscle as it expands and contracts could give feedback on the length of the muscle. A simple method was used to test this concept: measuring electrical resistance with using a voltage divider. We used a 100 kΩ resistor with the resistance of the water. We measured the voltage drop across the 100 kΩ resistor to find the resistance of the water at different distances. Figure 21 Shows this circuit setup.

![Figure 21: Circuit Setup for Water Resistivity Experiment](image)
We filled a 10 inch long tub with 100ml of tap water and measured the resistance in 1” increments from 0” to 9”. Appendix E has more information about how we calculated the resistance, and Section 5.1.2 has the results of the experiment.

4.3 Second Prototype: Constant Force Experiment

To test the final prototype, two types of test were performed. The constant force test was performed in much the same way as it was on the first prototype. The main difference being the new muscle was hooked up to its proprietary control system and could handle a wider range of pressures and weights. The muscle is suspended horizontally between two posts. One end of the muscle is held in place, while the other is tied to a string that runs over a pulley on the second post.Weights were tied at the end of the string to simulate the forces the muscle might experience during operation. For each experimental run, a different weight was attached. The muscle begins in equilibrium at atmospheric pressure. For each data point, the muscle pressure is recorded from the internal pressure gauge and the muscle length is measured with a yard stick. After each measurement, the valve between the muscle and running pump is opened for 1/20th of a second. The process is repeated until the muscle is fully extended. Figure 22 shows a photograph of this setup. Section 5.1.3 has the results of this experiment.
4.4 Second Prototype: Constant Length Experiment

For the constant length experiment, the muscle is once again suspended between the two posts, but this time both ends are affixed. At one end, there is a force transducer hooked up to Logger Pro. The muscle was stretched to several different lengths for each experimental run. The experiment begins with the muscle stretched to the given length at atmospheric pressure. For each data point, the muscle pressure is recorded from the integrated pressure gauge and the force is read from Logger Pro. For each successive measurement, the valve between the muscle and running pump is opened for 1/20th of a second. This is repeated until the muscle begins to sag from expansion (at which point the data would become unreliable). Figure 23 shows a photograph of this setup, and the results of this experiment can be found in Section 5.1.4.

![Figure 23: Setup of the Constant Length Experiment](image)

4.5 Muscle Resistance Experiment

The purpose of this experiment was to test the range of resistances we found in the water. We needed this so we could build a circuit that could take that resistance and convert it into an analog voltage that was readable by the Arduino’s 10-bit ADC. We needed, therefore, to convert the resistance to a range of 0 to 5 V. The Arduino’s ADC would then convert that voltage to a digital signal ranging from 0 to 1023. That number would be a proportional relationship to the length of the muscle. Our previous experiment demonstrated that resistance across a distance in water increases directly proportionally to the increase in distance. At this point, we wanted to know if we could use that property to measure the length of the muscle.

Our setup was similar to that other resistance experiment in that we used a known resistor and the resistance of the water as a simple voltage divider. We measured the voltage drop across the muscle in order to find the resistance. We used 12 Volts as
the supply voltage, because we were already using 12 Volts to power the solenoid valves. That way, our experiment would very closely resemble how the muscle would normally be situated; when we got the sensors working, we would use the 12 Volt supply voltage to produce the resistance across the muscle. Figure 24 shows the basic setup of the voltage divider. $V_{\text{measured}}$ shows the point at which we measured the voltage. We measured this voltage compared to the ground.

![Figure 24: Circuit Setup of Muscle Resistance Experiment](image)

After we set up this experiment, we proceeded by pumping water into the muscle and recording both the length of the muscle and the voltage difference between $V_{\text{measured}}$ and ground. This effectively gave us the voltage drop across the water inside the muscle.

We used the program, `open_close_valve_3.ino`, to open the muscle valves for 50 milliseconds and then close them again. This allowed a small amount of water to push into the muscle, extending the muscle by a short amount during every 50 millisecond-burst. The results of this experiment can be found in Section 5.1.5.
5 Results

5.1 Experiments

The complete data set from each of the experiments can be found in Appendix B.

5.1.1 First Prototype: Relationship between Length, Internal Pressure, and Force

The result of our first experiment was largely a success. The muscle functioned exactly as we had expected it to function. We were able to record the length of the muscle and the gauge pressure inside the muscle. There was a rather large concern with inaccuracy, however. We measured the pressure using the pressure gauge that comes with the bicycle pump. The gauge had increments of 10 pounds per square inch (PSI) marked, but nothing smaller than that. Because of the inaccuracy of the gauge we were using, we could only accurately estimate the pressure to within ± 5 PSI. Compounding that problem was the fact that, by all accounts, this setup was jury-rigged. The soda bottle we used as a reservoir had significant leaks in the top of it. This allowed the air to slowly escape, causing the pressure to continually decrease. We had to make our measurements as quickly as we could. The fact that there were inaccuracies with both the gauge and reading from the gauge meant that our pressure measurements were much closer to estimates. The full results can be seen in Figure 25.

![Chart 1: Results of First Prototype Experiment](image-url)
We can see on this graph that until the pressure reached close to 10 PSI, there was relatively no extension. Once it passed 10 PSI, it seemed that the length of the muscle increased proportionally to the internal pressure. We can see this in Figure 26.

![Chart 2](image)

Figure 26: Linear Results of First Experiment

What is interesting about this graph is just how linear the data points are. Each linear regression for each level of force has a correlation factor of greater than 0.99. While this may seem like very good news, it is important to keep in mind two facts. Firstly, the inaccuracies of the pressure readings mean that in all likelihood, what we read as a pressure is most likely not exactly correct. Secondly, in this graph, each force only has three data points. That is hardly something on which we can base any conclusions. It does, however, give enough confidence in understanding the nature of the relationship between the length of the muscle, the internal pressure, and the tensile force produced by the muscle.

5.1.2 Relationship between Electrical Resistivity of Water and Distance

This was another experiment that was largely successful. We tried to find the relationship between the distance between two probes and the resistance of the water. Our results showed a very linear relationship between the two. Figure 27 shows our final results: a plot of the resistance of the water with respect to the distance between the two submerged probes.
The major implication of this experiment was that we could calculate the length of the muscle at any given time simply by measuring the conductivity of the water. We knew that we would not be able to apply these exact results to our muscle, however. Because the water inside the muscle is in a very different environment than the basin of water we used for this experiment, the two would potentially have very different resistance for the same distance. We would have to specifically test the muscle resistance later on. What we got out of this experiment was the knowledge that the resistivity of water is directly proportional to the length of the water, and it gave us confidence that we could build a sensor to measure the length of the muscle.

5.1.3 Second Prototype: Constant Force Experiment

Like the previous experiment, we were varying the internal pressure in this experiment; unlike the previous experiment, we kept the force constant and measured the length of the muscle. This experiment was basically a retesting of the experiment we performed on the first prototype. We got fairly different results from this experiment than from when we used the first prototype. We did not get the same linear results. Figure 28 shows the results of keeping the force at 9.8 Newtons.
While it seems fairly linear after 15 PSI, which is similar to the results from the first prototype, what is interesting is what happens when you switch the axes. Figure 29 shows a more accurate relation of pressure to length, in the form of a polynomial regression. You can find all the data from this experiment in Appendix B.

5.1.4 Second Prototype: Constant Length Experiment

This experiment, like the experiment with the first prototype, was used to find a relationship between force, length, and pressure. This experiment kept the length constant, while increasing the pressure. Figure 30 shows that we found a linear
relationship between the tensile force exerted by the muscle and the pressure inside the muscle. This logically makes sense. As the pressure inside increases, it produces an outward force on the muscle. This counteracts the tensile force produced by the muscle when it is in tension. To see the full data set, you can see Appendix B.

![Figure 30: Results of Constant Length Experiment](image)

5.1.5 Muscle Resistance Experiment

This experiment was crucial in the failure of our attempt to use the conductivity of the water inside the muscle as a way to measure length. While the previous experiment to determine the relationship between the conductivity of water and distance was a success in that there was a linear correlation between the two, this experiment showed that we did not have enough time to successfully build a length sensor. Figure 31 shows the results of the resistance of the water inside the muscle at different lengths of the muscle.
There is not the same linear relationship between resistance and distance as there was when we performed the experiment with just a basin of water. The resistance seems to plummet at the start of the extension of the muscle, but then it steadily climbs upwards. Figure 32 shows that after the length of the muscle reaches about nine inches, the increase in resistance is very linear.

The conclusion we came was that between seven inches and nine inches, the elastic tube is expanding both radially and longitudinally. We think at the start of the
expansion the radial is much larger than the longitudinal expansion. As the length approaches nine inches, the radial expansion decelerates, and the longitudinal expansion increases. Once the length of the muscle is at about nine inches, the latex tube can no longer expand radially at all, so the muscle only extends longitudinally after that. This would account for the nonlinear decrease in resistance at the start and then the linear increase after nine inches.

This effect caused a large problem. Without a linear relationship, we did not have enough time to think of a way to design a circuit and program that could take the resistance and properly convert it into an accurate estimate of the length of the muscle. We were not able to build a length sensor because of these results.

5.2 Applications
There are various potential markets for a unique hydraulic exo-musculature design such as ours. We envision two potential applications of our specific hydraulic artificial muscle design: It can be used as exo-musculature and worn by people for various reasons, or it can be used in place of any rigid robotic muscle that currently exists. As exo-musculature, this design can be used in the health industry as a way to provide assistance and mobility to those that lack them, or it can be worn in order to augment a person’s strength.

5.2.1 Health Industry
There are a variety of uses for an exo-musculature design in the health industry. It can be used as prosthetics for people who have lost limbs. There are plenty of cases right now, where amputees are being given robotic limbs in place of their lost limbs. They have the ability now to control the movement of the robotic limb with their minds as accurately and as quickly as a human limb (Wickham, 2012). This hydraulic system is more compliant than rigid robotics and has the potential to move more similarly to human limbs than rigid robotic limbs.

It can be used in almost every aspect of physical therapy. It can be used to help a person regain movement after injuries. It can be used in the same manner to provide mobility and strength to people who have long been losing their mobility and strength. Because of its compliant nature, our hydraulic design would be much safer and much more applicable to human movement than any sort of rigid design.

5.2.2 Augmentation
The same way the muscle would be able to provide extra strength to those who have difficulty moving on their own, it could also provide augmented strength in other scenarios, too. Currently, the military is investing in powered, robotic exoskeletons in order to provide service men and women with super human strength (Ponsford, 2013). As advanced as these sorts of innovations are becoming, they have the same flaw in their rigidity as everything else. It is always going to have limitations in the degrees of freedom.
and mobility that comes with attaching another rigid structure to a human body. This design has the potential to produce the same large amounts of force as these military exoskeletons already do while being fluid and mobile and compliant enough to attach to a human body.

We do not just think that the potential for augmentation is limited to the military, though. We can see that if the musculature can be manufactured cheaply enough, it would be a useful product for laborers. If there is a job that you need a person for instead of a robot because there needs to be critical thinking involved, but the job also requires heavy lifting, this would be the perfect sort of environment that our design would be useful. It can augment a person’s strength, so you will only need one person to do tasks that require substantial amounts of heavy lifting.

5.2.3 Soft Robotics

Lastly, this design is not just confined to exo-musculature. There is nothing that limits this design to only being used on people. It potentially can perform just as well as an electric motor for virtually any robotic need. Because we designed this to be extremely modular, it can be used anywhere from industrial robotics to the robots that kids tinker with as a hobby. This has the potential to help move robotics as a whole away from rigid structures to soft robotics.

5.2.4 Cost

The thing that could really make this design popular is its affordability. We were able to construct three muscles for less than $10 apiece, and that was just in making a proof of concept. Granted, we have not done any sort of cost analysis or feasibility analysis, but its simple design with common materials lends itself to the idea that this design could potentially be one of the cheapest robotic products around. If a design were made such that all the parts were manufactured specifically for the muscle, the cost would drop dramatically from what we spent.
6 Conclusions

This hydraulic muscle is a unique design of our own invention. There is no artificial muscle existing right now which exhibits the capabilities that our design has. We were able to design and develop a proof on concept for a muscle which is potentially wearable by people due to its compliance and has the same ability to generate force as any other form of robotic muscle.

It is comprised of a tube made from elastic material surrounded by a soft, thin inelastic tube, preferably a plastic fabric such as polyester. The inelastic material is considerably longer than the elastic material, and it is wrinkled so that the ends of the elastic tube are matched with and attached to the ends of the inelastic tube. One end of the elastic tube is sealed shut, while the other is left open so that a fluid, preferably an incompressible one, can flow into it but not exit it. When more and more fluid is pumped into the tube, the pressure increases, and the elastic tube expands. The inelastic tube surrounding the elastic tube prevents the elastic tube from expanding radially to a large extent, so the elastic tube only elongates. The elastic material is able to elongate until it reaches the same length as the inelastic material.

By releasing the pressure inside the tube, the elastic material is able to contract, pushing out the fluid that was inside of it. This is the basic function of the muscle. It can produce a compressive force when it is being filled with fluid that is only limited to the gauge pressure of the fluid inside the tube. It also produces a tensile force, which is limited by the physical characteristics of the elastic material being used to make the inner tube.

This design is an improvement on previous artificial muscles, such as the McKibben muscle. The McKibben is pneumatically actuated, while our muscle is hydraulic. Because our design uses fluid which is incompressible, our muscle is potentially more energy efficient than a McKibben; the McKibben muscle will experience a loss of energy due to the compression of air at high pressures. Furthermore, our design almost completely constrains the extension and compression of the muscle to one dimension. While the McKibben works by inflating, causing the ends to move together, our muscle actuates solely in the longitudinal directions. In almost every aspect, our design is an improvement upon current fluid-actuated artificial muscles.

Because this is a unique design which we invented, we have applied for a patent through WPI. We also have a company, Liberating Technologies, which has shown interest in licensing our design from us for further development and use with prosthetics.

We were able to demonstrate its success at the Cambridge Science Festival on April 19, 2014. The system was running continuously for four hours with little children playing fairly roughly with the muscles. This demonstrates the safety and durability of the system while subject to constant human interaction. Granted, our design could not produce substantial amounts of force, as our main goal was to provide a proof of concept.
of the design. We were able to construct it such that it was robust enough that it never broke down and we had significant control over the muscles enough that it never malfunctioned. Further development can lead to stronger muscles that provide greater forces, which are just as safe to use as our proof of concept prototype.

Lastly, the biggest advantage our muscle design has over other forms of motors and artificial muscles is its potential for affordability. Each muscle in our proof of concept required less than $10 to build from scratch. A manufactured model would obviously reduce the costs much further. This, coupled with the understanding of our muscle’s compliance, means this design is an affordable method of soft robotics actuation. We believe that our design could potentially become a standard in future soft robotics because of these factors.
### Recommendations

The recommendations for the project arise from the problems faced during the assembly and operation of the system. Specifically, major disadvantageous issues were the size of the system, the leakage, and the low force output of the muscle.

Addressing these issues individually, one should notice that the size of the prototype is due to the crude nature of the project. During the design phase, our team focused on developing a good theoretical model for the system as well as presenting the muscle as a working prototype and a proof of concept; in essence, the main focus of the project was to develop and test the idea of the hydraulic muscle. For this reason the plumbing setup was a supplementary project and was not improved on. We managed to construct a system that provided enough of a flow rate for the muscle to operate robustly, thus satisfying one of the scopes of this project. Consequently, the plumbing system was basic and constructed out of common items found in the hardware store.

Considering the above, our first recommendation for future development is to reduce the size of the plumbing system. This is done in hope of developing a completely autonomous mobile system that can fit in a backpack. Particularly, a different pump of smaller dimensions and weight can be used, tube connectors can be eliminated, tube size can be reduced, fewer valves can be used (a 3 way valve could replace the T configuration) and finally the electronics can be compacted. This will require custom manufacturing of critical components, a task that we could not complete due to the limited resources available.

The next main issue of our system, as with any hydraulic system is the leakage. This occurs mainly due to pressure accumulation in critical points such as the connections. Water, being an incompressible fluid finds the way of least pressure to get to a point of equilibrium. The leaks in our system had to be completely eliminated and the prototype was not considered operational until they were fixed. This is due to the system being closed; in essence no fluid escapes. In addition, multiple critical electronic components could be affected by moisture or even a single droplet. These leaks occur due to the high tolerance inconsistencies of the threaded connections in our components. Considering, that most of the components were inexpensive and plastic threading was utilized, it was expected that leaks would occur.

In order to fix that problem, our team used common plumbing procedures and empirical practices. Specifically, we used Teflon tape to improve the threaded connections, as well as utilized the plastic to metal connections, as those are the most reliant against possible leaks. A recommendation for future development is to use custom parts with low tolerance inconsistencies and utilize new connection technologies such as the quick-connect. Generally, a neat system with original parts should not need any additional improvements such as the Teflon tape, and should be operational without any leaks.
The third main issue we had to face was improving the force output of the muscle; a task that was out of the objectives of our project. Seeing as we used inexpensive natural rubber latex, we could only achieve tensile force of 35 Newtons. While this is satisfactory, some improvements can be made. Specifically, a different material with better elastic properties could be used as the base tubing. We recommend the use of styrene-butadiene (SBR) synthetic rubber. This rubber is more readily available than natural rubber and exhibits better elongation and corrosion resistance.

Finally, we also faced issues with controlling the muscles. While the opening and closing delay times of the valves were adequate for a proof of concept, such cumbersome valve controls would not be acceptable in later generations of this design. Future generations would need to either buy or design their valves, which would not simply be either open or closed. In order to have full control over the muscles, it would be necessary to use a valve which can restrict the flow; they would need valves that act as variable resistors. In addition to the valves, we found future projects could try to construct sensors. With more work that is more heavily focused on the controls aspect of the design, there exists the potential to construct a muscle length sensor that actually functions.

**Problem**
- Size/Weight
- Leaks
- Low force output
- Lack of significant controls aspect

**Recommendations**
- Custom made parts
- High quality components/Low tolerance
- Better materials (stronger rubber)
- Use variable valves and incorporate sensors into the muscles
Works Cited


http://arduino.cc/en/Main/arduinoBoardUno


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Appendix A: Moment Calculations
Free-body diagram of the “forearm” and artificial muscle:

Free-body diagram legend:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>What it means</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{\text{Joint}}$</td>
<td>Force of the Joint</td>
</tr>
<tr>
<td>$F_{\text{Biceps}}$</td>
<td>Force of the Biceps</td>
</tr>
<tr>
<td>$W_{\text{Arm}}$</td>
<td>Weight of the Arm</td>
</tr>
<tr>
<td>$\Theta_1$</td>
<td>Muscle Angle of the biceps</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Flexion angle (From Vertical)</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Flexion Angle (From Horizontal)</td>
</tr>
<tr>
<td>$AP_1$</td>
<td>Biceps Attachment Point</td>
</tr>
<tr>
<td>$L_{\text{CoM}}$</td>
<td>Position of the Center of Mass of the Forearm</td>
</tr>
</tbody>
</table>
Triangle with sides and angles labeled:

Law of Sines:

\[
\frac{\sin a}{A} = \frac{\sin b}{B} = \frac{\sin c}{C}
\]

Law of Cosines:

\[
c^2 = A^2B^2 - 2AB \cos b
\]

Sum of the moments calculations:

\[
\sum M_{Elbow} = 0 = AP_1 \cos \beta \cdot F_{mussle} \sin(\theta + \beta) - AP_1 \sin \beta \cdot F_{mussle} \cos(\theta + \beta)
\]

\[
- L_{CoM} \cos \beta \cdot W_{arm}
\]

\[
0 = F_{mussle}[AP_1 \cos \beta \cdot \sin(\theta + \beta) - AP_1 \sin \beta \cdot \cos(\theta + \beta)] - L_{CoM} \cos \beta \cdot W_{arm}
\]

\[
F_{mussle} = \frac{(L_{CoM} \cdot W_{arm}) \cos \beta}{AP_1 \cos \beta \cdot \sin(\theta + \beta) - AP_1 \sin \beta \cdot \cos(\theta + \beta)}
\]

Sum of the forces in the x-dimension:

\[
\sum F_x = 0 = -F_{mussle} \cos \beta + F_{xJoint}
\]
Sum of the forces in the y-dimension:

\[ \sum F_y = 0 = F_{\text{muscle}} \sin \beta - F_{y\text{joint}} - W_{\text{arm}} \]

Solve for the moment arm:

\[ \frac{\sin 90}{AP_1} = \frac{\sin \theta}{\text{Moment Arm}} \]

\[ \text{Moment Arm} = AP_1 \cdot \frac{\sin \theta}{\sin 90} \]

\[ \text{Moment Arm} = AP_1 \sin \theta \]
Appendix B: Complete Experimental Data

First Prototype: Relationship between Length, Internal Pressure, and Constant Force

Chart 1

Chart 2

\[ y = 1.0625x + 1.8333 \quad R^2 = 0.9988 \]
\[ y = 0.8775x + 2.75 \quad R^2 = 0.9884 \]
\[ y = 0.6687x + 8.4333 \quad R^2 = 0.9986 \]
\[ y = 0.7909x + 7.1667 \quad R^2 = 0.9985 \]
\[ y = 0.7x + 9.0333 \quad R^2 = 0.9982 \]
Relationship between Electrical Resistivity of Water and Distance

This experiment measured the voltage drop across a distance of water, using a voltage splitter and a 100 kΩ resistor.
Second Prototype: Constant Length Experiment

Length = 16.25 in

\[ y = -0.78x + 26.838 \]
\[ R^2 = 0.9899 \]

Length = 16.25 in

\[ y = -0.8626x + 30.958 \]
\[ R^2 = 0.8833 \]
Length = 12 in

\[ y = -0.700x + 23.604 \]

\[ R^2 = 0.7879 \]
Second Prototype: Constant Force Experiment

Force = 9.8 N

\[
y = 0.2551x^2 - 4.4489x + 35.651
\]

\[R^2 = 0.9905\]
Force = 19.6 N

\[ y = 0.7091x^2 - 19.527x + 147.42 \]

\[ R^2 = 0.985 \]
Force = 24.5 N
Muscle Resistance Experiment

We used a voltage divider with a 135 kΩ resistor to determine the resistance of the muscle at different lengths.
Appendix C: Muscle Schematics

Basic Muscle Design

Relaxed

Expanded

Photograph of Second Prototype Muscle
Muscles Attached to Skeleton

Alternate Set up for Attachment to Skeleton
Here, we can see two muscles being used to actuate the elbow joint, and a third being used to actuate the shoulder.
Appendix D: System Design

Schematic

Photograph
## Pump Specifications

All information was taken from Pump Agents website (SHURflo, 2002).

### Pump Specifications:

<table>
<thead>
<tr>
<th>Model Number</th>
<th>8035-933-239</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump Design</td>
<td>Positive Displacement 3 Chamber Diaphragm Pump</td>
</tr>
<tr>
<td>Check Valve</td>
<td>(2-way Op.) Prevents Reverse Flow &amp; 6 Ft. Head Forward Flow</td>
</tr>
<tr>
<td>Cam</td>
<td>3.0 Degree</td>
</tr>
<tr>
<td>Motor</td>
<td>Permanent Magnor, P/N 11-223-00, Thermally Protected</td>
</tr>
<tr>
<td>Voltage</td>
<td>115 VAC Nominal</td>
</tr>
<tr>
<td>Pressure Switch</td>
<td>Adjustable Shut-Off (Range 140-160 PSI), Factory Set @ 150 PSI, Turn On 115 PSI</td>
</tr>
<tr>
<td>Liquid Temperature</td>
<td>180 Degrees Fahrenheit (82 Degrees Centigrade) Max.</td>
</tr>
<tr>
<td>Prime</td>
<td>Self-Priming Up to 6 Ft. Vertical, Max. Inlet Pressure 30 PSI</td>
</tr>
<tr>
<td>Ports</td>
<td>3/8&quot; - 18 NPT Female</td>
</tr>
<tr>
<td>Material of Construction</td>
<td>Nylon (Plastics), EPDM (Valves), Santoprene (Diaphragm), Zinc Plated Steel (Fasteners)</td>
</tr>
<tr>
<td>Net Weight</td>
<td>5.94 Lbs (2.7 Kg)</td>
</tr>
<tr>
<td>Duty Cycle</td>
<td>Intermittent</td>
</tr>
</tbody>
</table>

### Temperature Rise:

![Temperature Rise Graph](image-url)
Pump Schematic and Dimensions:

![Pump Schematic and Dimensions](image)

Photograph of Pump:

![Photograph of Pump](image)

Typical Performance Graph & Table:

![Typical Performance Graph & Table](image)
### Valve Specifications

**Connection**
- 1/2'' Nominal NPS

**Working Pressure**
- 0.02 MPa - 0.8 MPa

**Working Temperature**
- 1°C to 75°C

**Response time (open)**
- ≤ 0.15 sec

**Response time (close)**
- ≤ 0.3 sec

**Actuating Voltage**
- 12VDC

**Actuating Life**
- ≥ 50 million cycles

**Weight**
- 122 grams

**Dimensions**
- 3'' x 2.25'' x 2''
Appendix E: Circuit Diagrams

Water Resistivity Circuit

This was the voltage divider set up used to measure the resistance of the water at different values of $x$. The voltage drop measured across the 100 kΩ resistor was used to determine the resistance of the water across the distance, $x$, $(R_x)$ using the formula:

$$V_{measured} = 5 \left( \frac{100000}{100000 + R_x} \right)$$

Differential Amplifier Circuit

This image is courtesy of allaboutcircuits.com (Alphas, 2007)

If $R_2 = R_1$ and $R_f = R_g$, then:

$$V_{out} = (V_2 - V_1) \left( \frac{R_f}{R_1} \right)$$
Sensor Circuit

After determining the values of $R_{\text{sense(min)}}$ & $R_{\text{sense(max)}}$ through testing, find values for $R_2$ & $R_1$, such that:

$$\frac{R_2}{R_1 + \frac{R_{\text{sense(min)}}}{2}} = \frac{5}{V_{\text{CC}} \left( \frac{R_{\text{sense(min)}}}{R_{\text{sense(max)}} + R_{\text{sense(min)}}} \right) - \frac{V_{\text{CC}}}{2}}$$

$V_{\text{CC}} \left( \frac{R_{\text{sense(min)}}}{R_{\text{sense(max)}} + R_{\text{sense(min)}}} \right)$ represents the voltage coming from the voltage divider at the top of the diagram.

$\frac{V_{\text{CC}}}{2}$ represents the voltage coming from the voltage divider at the left of the diagram.

$\frac{R_{\text{sense(min)}}}{2}$ represents an approximation of the Thévenin equivalent resistance for both voltage dividers. So:

$R_1 + \frac{R_{\text{sense(min)}}}{2}$ represents what $R_1$ is in a basic differential amplifier circuit. See the previous section in this Appendix.
12-V Valve Circuit

When a 5 Volt signal is sent to the base pin (labeled B), the current is able to flow from the collector pin (labeled C), through the BJT, and to the emitter pin (labeled E). This allows the 12 Volt difference to open the solenoid valve.

Muscle Resistance Circuit

This is another simple voltage divider circuit, used to measure resistance. It follows the equation:

\[ V_{\text{measured}} = 12 \left( \frac{R_{\text{MUSCLE}}}{R_{\text{MUSCLE}} + 135000} \right) \]
Appendix F: Code
All code snippets were written in C++.

open_close_valve.ino
This code simply turns a single valve, connected to digital I/O port 13, on and off using the keyboard inputs from the user.

const int valvePIN = 13;
int valveState = LOW;

void setup() {
    Serial.begin(9600);
    pinMode(valvePIN, OUTPUT);
    Serial.println("Press '1' to open valve, and press '2' to close valve.");
    Serial.println("Press '0' for valve state inquiry.");
    Serial.println("Valve is initially closed.");
}

void loop() {
    if (Serial.available() > 0) {
        char inChar = Serial.read();
        if (inChar == '1') {
            if (valveState == LOW) {
                valveState = HIGH;
                Serial.println("Valve is now open.");
            }
            else if (valveState == HIGH) {
                Serial.println("Valve is already open.");
            }
        }
        else if (valveState == HIGH) {
            Serial.println("Valve is already open.");
        }
        else if (inChar == '2') {
            if (valveState == LOW) {
                Serial.println("Valve is already closed.");
            }
            else if (valveState == HIGH) {
                valveState = LOW;
                Serial.println("Valve is now closed.");
            }
        }
        else if (inChar == '0') {
            Serial.print("Valve is ");
            if (valveState == HIGH) {
                Serial.println("OPEN");
            }
            else if (valveState == LOW) {
                Serial.println("CLOSED");
            }
        }
    }
}
else if (valveState == LOW) {
    Serial.println("CLOSED");
}

digitalWrite(valvePIN, valveState);
open_close_valve_2.ino
This code toggles all six valves, connected to digital I/O ports 8 through 13

const int valvePIN1 = 13;
const int valvePIN2 = 12;
const int valvePIN3 = 11;
const int valvePIN4 = 10;
const int valvePIN5 = 9;
const int valvePIN6 = 8;
int valveState1 = LOW;
int valveState2 = LOW;
int valveState3 = LOW;
int valveState4 = LOW;
int valveState5 = LOW;
int valveState6 = LOW;

void setup() {
  Serial.begin(9600);
  pinMode(valvePIN1, OUTPUT);
  pinMode(valvePIN2, OUTPUT);
  pinMode(valvePIN3, OUTPUT);
  pinMode(valvePIN4, OUTPUT);
  pinMode(valvePIN5, OUTPUT);
  pinMode(valvePIN6, OUTPUT);
  Serial.println("Press '1' to toggle valve 1, \n\n\npress '2' to toggle valve 2, \n\npress '3' to toggle valve 3, \n\npress '4' to toggle valve 4, \n\npress '5' to toggle valve 5, \n\nrand press '6' to toggle valve 6.");
  Serial.println("Press '0' for valve state inquiry.");
  Serial.println("\nValves are all initially closed.");
}

void loop() {
  if (Serial.available() > 0) {
    char inChar = Serial.read();
    if (inChar == '1') {
      if (valveState1 == LOW) {
        valveState1 = HIGH;
        Serial.println("Valve 1 is now open.");
      }
      else if (valveState1 == HIGH) {
        valveState1 = LOW;
        Serial.println("Valve 1 is now closed.");
      }
    }
  }
}
else if (inChar == '2') {
    if (valveState2 == LOW) {
        valveState2 = HIGH;
        Serial.println("Valve 2 is now open.");
    }
    else if (valveState2 == HIGH) {
        valveState2 = LOW;
        Serial.println("Valve 2 is now closed.");
    }
}
else if (inChar == '3') {
    if (valveState3 == LOW) {
        valveState3 = HIGH;
        Serial.println("Valve 3 is now open.");
    }
    else if (valveState3 == HIGH) {
        valveState3 = LOW;
        Serial.println("Valve 3 is now closed.");
    }
}
else if (inChar == '4') {
    if (valveState4 == LOW) {
        valveState4 = HIGH;
        Serial.println("Valve 4 is now open.");
    }
    else if (valveState4 == HIGH) {
        valveState4 = LOW;
        Serial.println("Valve 4 is now closed.");
    }
}
else if (inChar == '5') {
    if (valveState5 == LOW) {
        valveState5 = HIGH;
        Serial.println("Valve 5 is now open.");
    }
    else if (valveState5 == HIGH) {
        valveState5 = LOW;
        Serial.println("Valve 5 is now closed.");
    }
}
else if (inChar == '6') {
    if (valveState6 == LOW) {
        valveState6 = HIGH;
        Serial.println("Valve 6 is now open.");
    }
else if (valveState6 == HIGH) {
    valveState6 = LOW;
    Serial.println("Valve 6 is now closed.");
}
}
else if (inChar == '0') {
    Serial.print("Valve 1 is ");
    if (valveState1 == HIGH) {
        Serial.print("open.");
    }
    else if (valveState1 == LOW) {
        Serial.print("closed.");
    }
    Serial.print("Valve 2 is ");
    if (valveState2 == HIGH) {
        Serial.print("open.");
    }
    else if (valveState2 == LOW) {
        Serial.print("closed.");
    }
    Serial.print("Valve 3 is ");
    if (valveState3 == HIGH) {
        Serial.print("open.");
    }
    else if (valveState3 == LOW) {
        Serial.print("closed.");
    }
    Serial.print("Valve 4 is ");
    if (valveState4 == HIGH) {
        Serial.print("open.");
    }
    else if (valveState4 == LOW) {
        Serial.print("closed.");
    }
    Serial.print("Valve 5 is ");
    if (valveState5 == HIGH) {
        Serial.print("open.");
    }
    else if (valveState5 == LOW) {
        Serial.print("closed.");
    }
    Serial.print("Valve 6 is ");
    if (valveState6 == HIGH) {
        Serial.println("open.");
    }
else if (valveState6 == LOW) {
    Serial.println("closed.");
}

digitalWrite(valvePIN1, valveState1);
digitalWrite(valvePIN2, valveState2);
digitalWrite(valvePIN3, valveState3);
digitalWrite(valvePIN4, valveState4);
digitalWrite(valvePIN5, valveState5);
digitalWrite(valvePIN6, valveState6);
open_close_valve_3.ino

This program uses keys 1, 2, and 3 to determine what to do. If ‘1’ is pressed, the valves connected to the muscles (i.e., digital I/O ports 1, 3, and 5) open for 50 milliseconds and then they close. If ‘2’ is pressed, it toggles the release valves (i.e., digital I/O ports 2, 4, and 6). If ‘3’ is pressed, the release valves open for 50 milliseconds before closing again.

const int valvePIN1 = 13;
const int valvePIN2 = 12;
const int valvePIN3 = 11;
const int valvePIN4 = 10;
const int valvePIN5 = 9;
const int valvePIN6 = 8;
int releaseValvesState = LOW;

void setup() {
  Serial.begin(9600);
  pinMode(valvePIN1, OUTPUT);
  pinMode(valvePIN2, OUTPUT);
  pinMode(valvePIN3, OUTPUT);
  pinMode(valvePIN4, OUTPUT);
  pinMode(valvePIN5, OUTPUT);
  pinMode(valvePIN6, OUTPUT);
  Serial.println("Press '1' to open valves for 0.05 seconds.");
  Serial.println("Press '2' to toggle release valves.");
  Serial.println("Press '3' to open release valves for 0.1 seconds.");
  Serial.println("Press lowercase 'l' to see the length of the muscle.");
  Serial.println("\nValves are initially closed.");
}

long num = 0;
int i;

void loop() {
  if (Serial.available() > 0) {
    char inChar = Serial.read();

    if (inChar == '1') {
      digitalWrite(valvePIN1, HIGH);
      digitalWrite(valvePIN3, HIGH);
      digitalWrite(valvePIN5, HIGH);
      Serial.println("Valves are open.");
      delay(50);
digitalWrite(valvePIN1, LOW);
digitalWrite(valvePIN3, LOW);
digitalWrite(valvePIN5, LOW);
Serial.println("Valves are closed.");
}
else if (inChar == '2') {
        if (releaseValvesState == HIGH) {
                releaseValvesState = LOW;
                Serial.println("Release valves are now closed.");
        }
        else if (releaseValvesState == LOW) {
                releaseValvesState = HIGH;
                Serial.println("Release valves are now open.");
        }
}
else if (inChar == '3') {
        digitalWrite(valvePIN2, HIGH);
digitalWrite(valvePIN4, HIGH);
digitalWrite(valvePIN6, HIGH);
Serial.println("Release valves are open.");
delay(50);
digitalWrite(valvePIN2, LOW);
digitalWrite(valvePIN4, LOW);
digitalWrite(valvePIN6, LOW);
Serial.println("Release valves are closed.");
}
else if (inChar == 'l') {
        for (i=0 ; i<10 ; i++) {
                num = num + analogRead(A0);
delay(10);
        }
        Serial.println(int(num/10));
        num = 0;
}
else {
        Serial.println("No action.");
        digitalWrite(valvePIN2, releaseValvesState);
digitalWrite(valvePIN4, releaseValvesState);
digitalWrite(valvePIN6, releaseValvesState);
}
pid.ino

This code is unfinished. I wrote it originally so that it could interface with the user in such a way that they would choose the angle of the bicep to go to. Using the length sensor information from the analog input pin, this code runs a PID feedback loop. The things that needed to be fixed on it included tuning the PID constants, switch out `pid1` function for `pid` function (The latter was the real PID loop, while the former was just for demonstration purposes.), and adjusting the `getAngle` function. The PID works by sending a pseudo-PWM signal to the valves. Since I could not use real PWM such as with an electric motor, I have the valve open for a certain amount of time which is determined by the PID loop. After that, it closes for a tenth of a second. After that it, reads from the length sensor and run through the loop again until it reaches its destination. It certainly does not work the same way a PID loop would with a PWM signal, but I figured this was the best way to get some kind of feedback loop. Unfortunately, it took too long to construct the entire hydraulic system, so I never was able to tune and get my pseudo-control system working.

```cpp
int valve1PIN = 13;
int valve2PIN = 12;
int lengthPIN = A0;

void setup() {
    Serial.begin(9600);
    pinMode(valve1PIN, OUTPUT);
    pinMode(valve2PIN, OUTPUT);
}

long P = 1;
long I = 1;
long D = 1;

int num = 0;
int thisNum;
int currAngle = 0;
int state = 0;

void loop() {
    Serial.println("Give angle of arm. Press 'Enter' key when finished.");
    while (Serial.available() <= 0){
        delay(1);
    }
    state = 1;
    while(state == 1) {
        if (Serial.available() > 0) {
```
int input = Serial.read();
if (input == 13) {
    Serial.println(""");
    Serial.print("Desired Angle is: ");
    Serial.println(num);
    pid1(num);
    num = 0;
    state = 0;
}
else if (input == 127) {
    num = num/10;
    Serial.print(char(input));
    // Serial.print("\r");
    // Serial.print(num);
}
else if (input >= 48 && input < 58) {
    thisNum = input - 48;
    Serial.print(char(input));
    num = num*10 + thisNum;
} else {
    Serial.println(""");
    Serial.println("Please do not give characters which are not numbers.");
    Serial.print(num);
}
}

void pid1(int desiredAngle) {
    Serial.print("Current Angle is: ");
    Serial.println(currAngle);
    if (desiredAngle >= currAngle) {
        while (currAngle != desiredAngle) {
            currAngle ++;
            Serial.print("Current Angle is: ");
            Serial.println(currAngle);
        }
    } else if (desiredAngle < currAngle) {
        while (currAngle != desiredAngle) {
            currAngle --;
            Serial.print("Current Angle is: ");
            Serial.println(currAngle);
        }
    }
Serial.println("Reached Desired Angle");
Serial.println(currAngle);

void pid(int desiredAngle) {
  int sumError = 0;
  int prevError = 0;
  int diffError = 0;
  currAngle = getAngle(lengthPIN);
  Serial.print("Current Angle is: ");
  Serial.println(currAngle);
  while (desiredAngle != currAngle){
    int currError = desiredAngle - currAngle;
    int diffError = currError - prevError;
    int pid = currError*P + sumError*I + diffError*D;
    if (pid > 0) {
      openValve(valve1PIN, pid);
    } else if (pid < 0) {
      pid = pid*-1;
      openValve(valve2PIN, pid);
    }
    prevError = currError;
    sumError += currError;
    delay(100);
    currAngle = getAngle(lengthPIN);
  }
}

void openValve(int pin, int duration){
  digitalWrite(pin, HIGH);
  delay(duration);
  digitalWrite(pin, LOW);
}

int getAngle(int pin){
  // This will scale the 0 to 1023 input values to 5 to 180 degree usable values
  long sensorValue = analogRead(pin);
  long degree = 5 + sensorValue/5.84;
  return int(degree);
}
//TODO: Change the PID to work!!!!!!