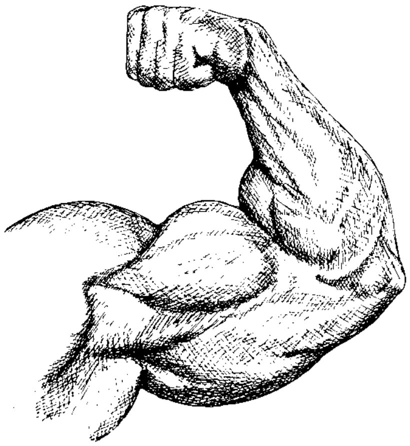


# Untethered Hydraulic Artificial Muscle Elbow Exoskeleton

ME 47400
May 22nd 2020
Prof. James Hammonds

***Sponsor: Dr. Hao Su***


By*

Mahnoor Azim | - | - | - | - | - | - | -

*Team Leader*: -


**Names redacted for confidentiality purposes*

**Summary**

This project involved the creation of an untethered hydraulic artificial muscle (HAM) elbow exoskeleton. The design objectives were to restore functionality of the previously designed HAM system, implement it into a wearable structure, and make it portable. The device is composed of the artificial bicep muscle, a hydraulic pump, a brushless motor, hydraulic fluid, an electronic speed controller, a shoulder harness, a forearm strap, a fanny pack, oil storage pouches, a power supply, and D-rings. The system becomes portable when the power supply is swapped out for batteries, and oil is supplied from storage pouches in the fanny pack instead of the oil reservoir. The system operates by first supplying power either through batteries or a DC power supply. Next the code for the controller is executed, which runs through a loop of increasing voltage to power up the motor. The motor then powers the hydraulic pump to supply the muscle with hydraulic fluid, causing it to contract. This process allows for the muscle to be powered by the user when needed; the artificial muscle contracts to lift the user’s elbow. Design constraints in this project were related to the comfortability of the system’s user. Constraints were the overall mass of the system being less than 2.5 kilograms and the use of soft materials to prevent skin adversities. No significant limitations were observed.

## Table of Contents

## Introduction

This project's goal is to assist people with medical issues and those who work in a strenuous job environment. Medical issues to be relieved by this exoskeleton include people with muscle weakness or muscle damage, whether it be physical damage or nerve damage; use could also be suitable for rehabilitation. The strenuous jobs targeted for the use of this exoskeleton include construction, warehouse workers, mechanics, and any other job environment where frequent heavy lifting is involved.

**Problem Statement and Objectives**

The general requirement of this project is to design a soft wearable structure for a hydraulic artificial muscle (HAM), being used for an elbow exoskeleton. Specific requirements include to make the elbow exoskeleton untethered and portable. That is, it must be wearable and functional outside of the laboratory setting. The requirement where the engineers must be most creative lies in the addition of a portable pumping system to the exoskeleton system. The pumping system must contain an oil reservoir, pump, motor, motor driver, Arduino, the housing for the system, and must not obstruct user movement. The pump system must be safe to wear, perform properly, easy to clean, and comfortable to wear. The final requirement is to ensure that the mass of the entire exoskeleton, including the wearable structure, is less than 2.5 kilograms because it is not ideal for the user to be carrying something that would impede them from moving normally. It is important to note that the efficiency of the system is not of concern.

## Product Design Specifications

### *Design Problems*

The design problems associated with this project arise from making the system portable. This is due to the need of having a pressurized oil reservoir. Having a portable oil reservoir means there are more chances of having a leak and the material being used must be able to withstand frequent changes in pressure. Additionally, the team had to find a way to improve the wearable structure that was made. That is, the team considered that each individual has a different arm size and we needed to make an arm support that would conform to the user's arm while being comfortable. Another issue with making a portable system is power supply. Portable power supply would include batteries which could contribute to a significant mass increase of the system. Lastly, portability of the system would involve having to shield the motor driver and pump to ensure there is no interaction between them and the outer environment. This is to both protect the user and both components, again leading to an increase in mass of the system. These design problems will pose a challenge in meeting the mass requirement of the sponsor.

### *Operation*

There are many operating environments for the HAM elbow exoskeleton. The first is a clinical setting such as in a hospital or nursing home for physical rehabilitation. The second is in a physical labor field, where the exoskeleton can be used if heavy lifting must be done by a human. A third possible setting for the HAM elbow exoskeleton is a private setting, such as if an individual is a soft robotics enthusiast and wants to have one of these systems at home. The special features of the HAM Exoskeleton system will be “soft” robotics, and naturally compliant materials that play a crucial role to minimize rigid parts. In doing so, we mimic what happens in human motion and it will be easy to practice passive and active motions, which is ideal for exoskeletons.

### *Maintenance*

The team came to the conclusion that we would like the economic life of the HAM Exoskeleton to be five to ten years. However, it can only last this long if minor and major maintenance is done. Minor maintenance will be every month and includes checking for wear and tear every 1-2 months and cleaning/replacing hydraulic fluid for the muscles pump. Major maintenance will be done once a year and includes replacing the tubing, straps, pressure valves, and instrumentation devices every 12 months. The retirement of the elbow will be after 5-10 years and there is a possibility to even recycle parts from retired devices. We have not forgotten to take into account the Reliability and Robustness of the system. Our HAM elbow exoskeleton will withstand high workload (cycles) in its 5-10 year lifespan, which is an average of 224,000 cycles per week.

### *Safety*

In regards to safety, the primary concern is that the exoskeleton does not cause any type of injury such as abrasions and/or bruises while being operated. It is also important to consider that the exoskeleton should be designed so it does not apply a force that the user cannot handle. This would also be intertwined with the idea that the muscle is able to assist a user in lifting their arm without the cramping of limbs and production of stress on joints. Another factor to take into account is the portable pump system safety, meaning the pump must operate at optimal pressures and voltages so that the HAM can function properly; if the pump performs poorly the HAM can either be not pumped with enough oil, or be pumped with too much and risk the muscle exploding. The team plans on the implementation of a pressure sensor for a digital readout of the pumping pressure so the user knows if there is a problem that needs to be addressed.

### *Ease of Use*

Ease of use is a crucial factor in deciding whether or not a design is successful. This is because ease of use affects how the product will be used; a product that is easy to use means it will be operated properly which means less chance of injury, proper use means less wear and stress on the exoskeleton which enhances product life, and a product that is easy to use generates customer satisfaction due to minor input for use. The ease of use factor in this exoskeleton is its easy ability to turn on and off, along with being easy to wear and remove.

## Design Concepts

*Subsystem Flow Chart*

The figure below shows the subsystems for the exoskeleton. The main function of the exoskeleton is to provide support to the user. From there, the functions can be split into three main parts. The first is that it is supposed to mimic the movement of an elbow. It does this through an attachment from the forearm to the hydraulic muscle. It then lifts the user's forearm, creating rotation in the elbow. The second function of the exoskeleton is to house the hydraulic muscle. Housing the muscle is important because it is acting as the actuator in this exoskeleton and enables movement in the arm. The last subsystem focuses on convenience. The exoskeleton must be adjustable and portable.

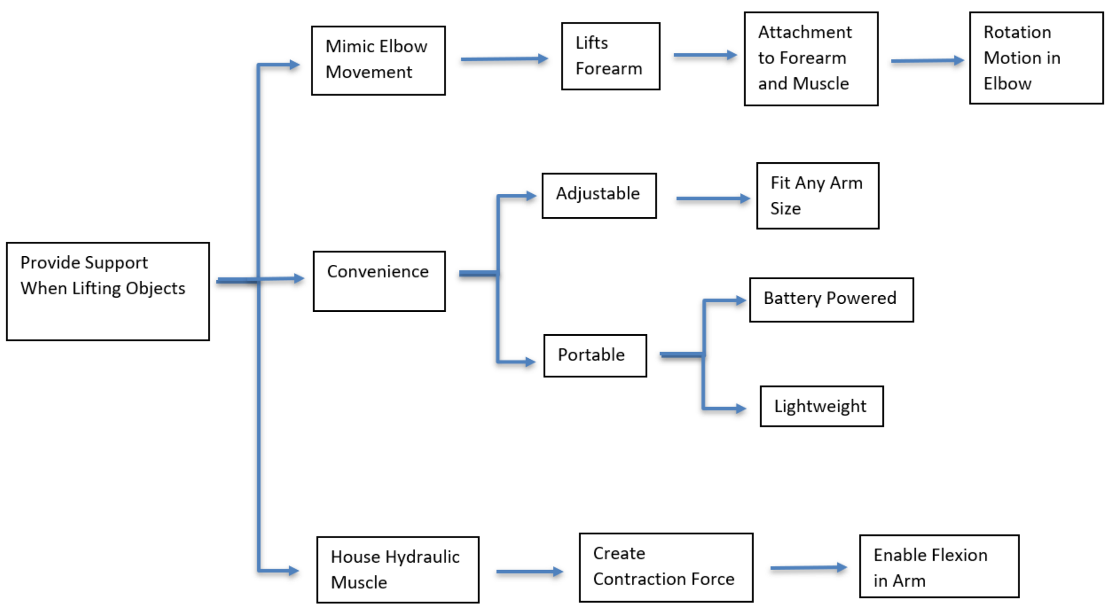



***Fig. 1** – The subsystem flowchart.*

## Design Concepts

### *Design 1*

Based on the design requirements given by our sponsor, our team came up with a number of design concepts. For our first concept, a design was made that utilized one muscle. A single hydraulic muscle was made the previous year so naturally, that is where our thoughts for design went first. Another factor that went into our design was the fact that our sponsor wanted soft, lightweight materials to be used that wouldn't be heavy or hinder any natural arm movement for the user. The design consists of a shoulder harness, an adjustable forearm strap, the artificial muscle and the pumping system. The shoulder harness was chosen so that the muscle would have an anchor when contracting and the muscle would be attached using D-rings that would be sewn on to the harness and forearm strap.

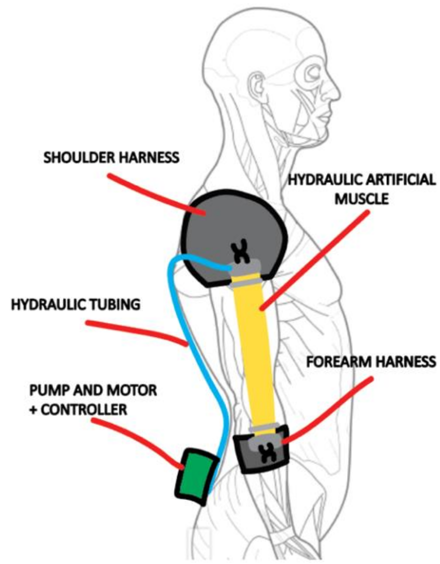



***Fig. 2** – Design 1 schematic.*

### *Design 2*

The second design is very similar to the first one. This design would utilize the same shoulder harness and forearm strap design. The difference with this design is that there are two muscles. This design was inspired by studying how the muscles in the arm create movement in the elbow during flexion and extension. For this design, one muscle would act as a bicep, the other would act as the tricep. While one contracts, the other would extend, creating an up and down motion.

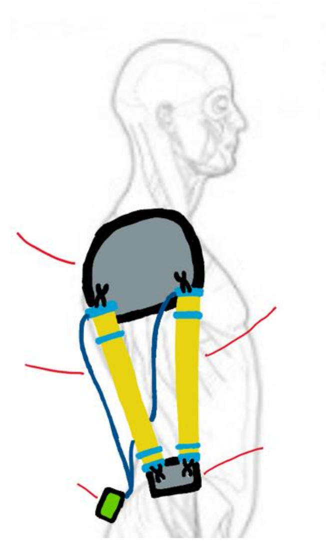


***Fig. 3** – Design 2 schematic.*

*Design 3*

The last design concept again uses the same strapping to attach the muscle to the user's arm. This design consists of many muscles that go all the way around the users arm. The muscles would have a smaller diameter than the original muscle and having them spread out around the arm would allow for a more uniform lifting motion.

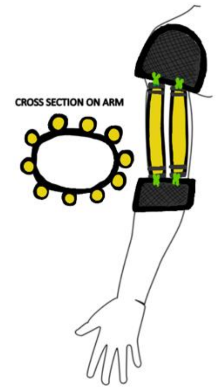



***Fig. 4*** *– Design 3 schematic.*

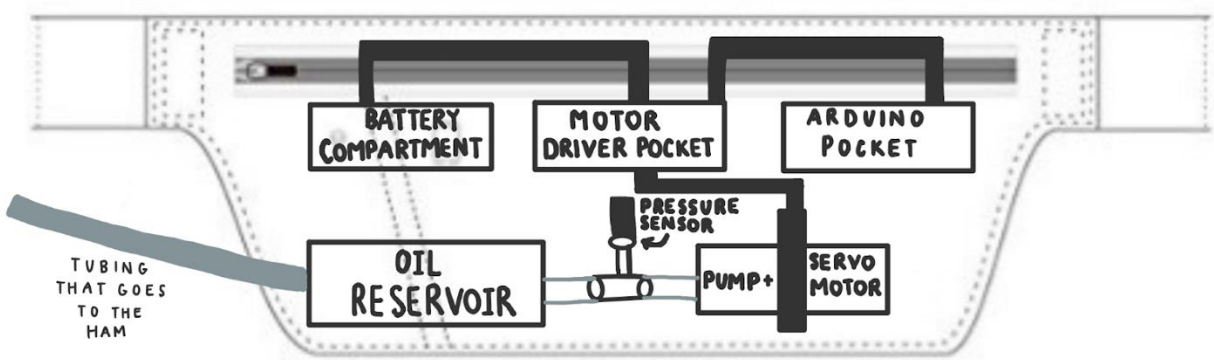



***Fig. 5*** *– Pumping system pouch design with interior layout of components.*

A design to make the current pumping system portable was also made. This consists of a pouch that would rest on the user's lower back. The pouch will have a series of compartments that will house the battery, motor driver and the controller. The bottom of the pouch will contain the oil reservoir and the pump and servo motor. In order to account for the servo motor's spinning motion, a separate compartment will have to be made (probably 3D printed). This compartment will hold the motor steady, while also allowing it to spin and not get tangled in any wires or tubing in the pouch.

*Design Matrix*

The concepts were put into a design matrix and compared with each other. The matrix is shown in the table below. The weights for the criteria were chosen on a scale of 1-3, with 1 being of lower importance and 3 being of utmost importance. Each design was given a +, - or 0 for each criteria. + being positive, 0 being neutral and - being negative.

*Table 1*: Design Matrix Chart for the 3 Different Design Concepts

| *Concepts* | | *One Muscle* | *Two Muscles* | *Multiple Muscles* |
|---|---|---|---|---|
| *Criteria* | Weight | | | |
| **Cost** | 1 | + | - | - |
| **Technical Difficulty** | 2 | + | - | + |
| **Range of Motion (0-150)** | 3 | + | + | + |
| **Weight ( < 2.5 kg)** | 2 | + | - | + |
| **Flexion Ability** | 3 | + | + | + |
| **Extension Ability** | 1 | - | + | - |
| **Universal** | 2 | + | + | + |
| **Ease of Use** | 2 | + | + | + |
| **Portable** | 3 | + | + | - |
| **Overall Total** | | ***7*** | ***3*** | ***3*** |
| **Weighted (+)** | | 18 | 14 | 14 |
| **Weighted (-)** | | 1 | 5 | 5 |
| **Weighted Total** | | ***17*** | ***9*** | ***9*** |

There are certain criteria that were weighted more than others. The range of motion, flexion ability and portability were criteria given explicitly by our sponsor so those were weighted the most. For portability, the concept with multiple muscles got a - due to the fact that that design would require a lot of tubing and possibly a larger pump and oil reservoir, hindering the ability to make the exoskeleton portable. The technical difficulty was also an important factor that was taken into account. For example, the design concept that utilizes two muscles would be more difficult to accomplish technically. Programming the Arduino to make the two muscles work opposite to each other could be difficult and it would possibly require the use of two pumping systems.

*Concept Selection*

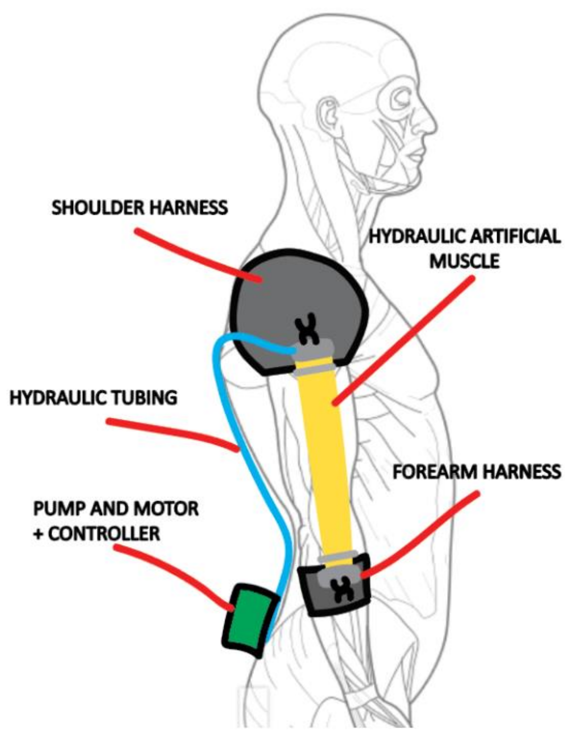



***Fig. 6*** *– Final selected design concept: design 1.*

After inputting the designs into the design matrix, the first concept, the exoskeleton that utilizes one muscle, won over all the other designs. It was the least expensive option and the simplest for our team to accomplish within the spring semester.

## Analysis and Testing

Throughout the assembly process for the final product, each part was tested and analyzed to make sure it was good for use. The analytical data for the muscle system was collected using a series of sensors and Arduino software. Using the program that was given for the muscle, the code was run for the motor pump with an external sensor which recorded the pressure inside the tubing. Modifying the program to include the sensor, a chart was produced showing the variation in pressure distribution during the time in which the motor was on. The results as shown in the figure below, were obtained by converting the voltage received by the attached pressure sensor. In the graph, the pressure reaches a steady state of approximately 36 psi which is the pressure value at which the HAM stops contracting. After this steady state phase, a dramatic drop can be seen corresponding to the moment when the power to the motor is cut off.

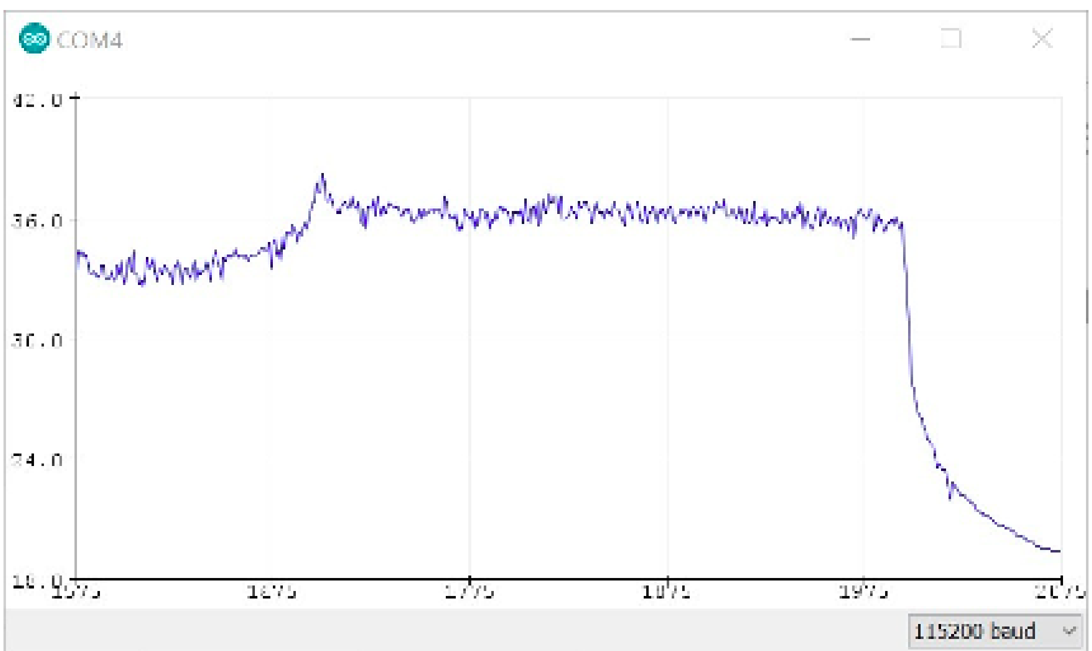



***Fig. 7*** *– Chart depicting pressure output received from the Arduino.*

After assembling the finalized concept for the model, several tests were conducted to see if the exoskeleton would perform the way it was intended to and whether the wearability was sufficient enough for a common user. The straps and overall design fit well with adjustments to the model's build. The material selections and placement proved to be a good fit for the concept. When running the motor system with the exoskeleton attached to the test subject, results showed that the arm did indeed get pulled up by the muscle as it contracted, however it was very limited due to the short amount of contraction. Although the contraction and height of pull was very small, the exoskeleton still did a sufficient job at performing its programmed task.

Further studies were conducted to determine the maximum amount of weight the muscle would be able to carry. Based on the data previously collected, our assumption was that the maximum would be around 36 psi, which was the pressure value in the system at the time of the muscle fully contracted. An experiment was set up consisting of a bucket of water weighing a total of 38 lbs. During the course of the test, the muscle seemed to have lifted the substantial weight successfully off the ground, however it eventually ruptured shortly after. The rupture instance can be seen in the figure below. Due to a larger amount of weight than the perceived cutoff pulling down on the HAM, the high pressure buildup inside the tubing led to the endcap popping off the end, resulting in failure.

***Fig. 8*** *– Hydraulic muscle lifts up the 38 lb. bucket of water, just before it ruptures.*

The previous team who designed the muscle system, did multiple tests with different designs for endcaps that would better hold the muscle in place, since the main mode of failure for rupture is by the loosening of the endcap. Different iterations were made and the most promising design was the one that was used for this exoskeleton. Since our main focus for this project was the exoskeleton design, no further testing was performed on the endcap design or various parts of the muscle itself. Future examination for the design of the endcaps and mechanism of the muscle, may actually enhance the HAM exoskeleton's function.

***Fig. 9*** *–Different iterations of the endcap. The one on the right is the current design.*

Currently, the HAM only has the ability of contracting 1 inch in length. This means that although it has the strength to lift a considerable amount of weight, it can only raise up 1 inch and no more. In order for it to be in effective use, the total contracted length should be improved upon in future testing. An increase in the length of contraction may lead to an increase in the maximum amount of weight that it is able to withstand, thus improving overall performance.

## **Product Architecture**

The exoskeleton can be broken down into two main systems, the pump and the wearable structure. Broken down further, the pumping system can be broken down into the battery, controller and the pump itself. The wearable structure encompasses the hydraulic artificial muscle and the harness system that was created to attach the muscle to the user's body. The figure below shows a diagram of the system and how each of the components connect with each other.

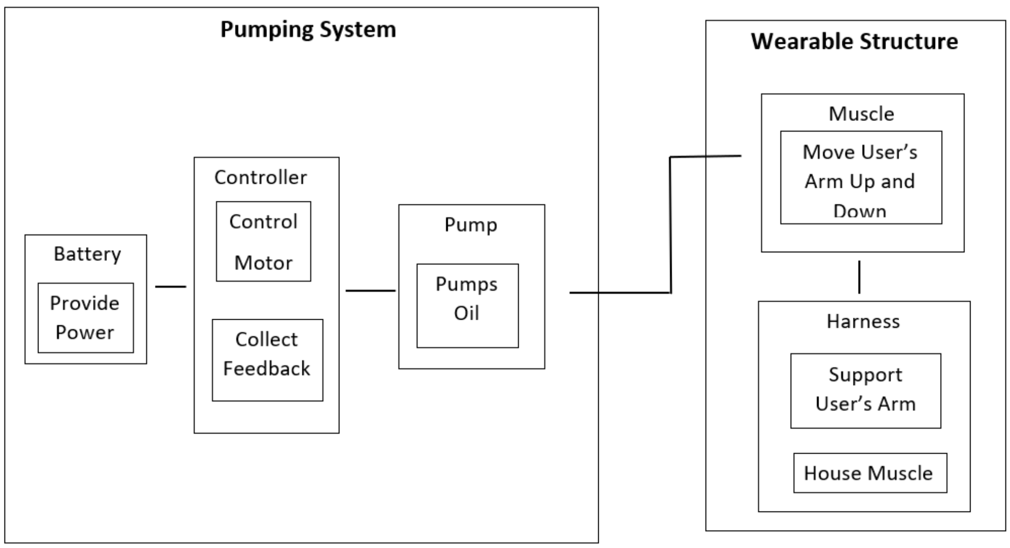



***Fig. 10*** *– Diagram of the two main systems comprising the HAM exoskeleton.*

All of the components that make up the two main systems of the exoskeleton can be seen in Figure 11, each component has a specific purpose. The power sources are what will be discussed first. During our testing phases we used a power source that plugged into a wall that powered the motor driver for the system. In order to make the assembly untethered we planned to use batteries as an electric source; the Arduino would need a 9V battery and the ESC motor driver would need two rechargeable 12V batteries connected in series, giving a voltage of 24V. The brushless DC motor was chosen because of its high torque.

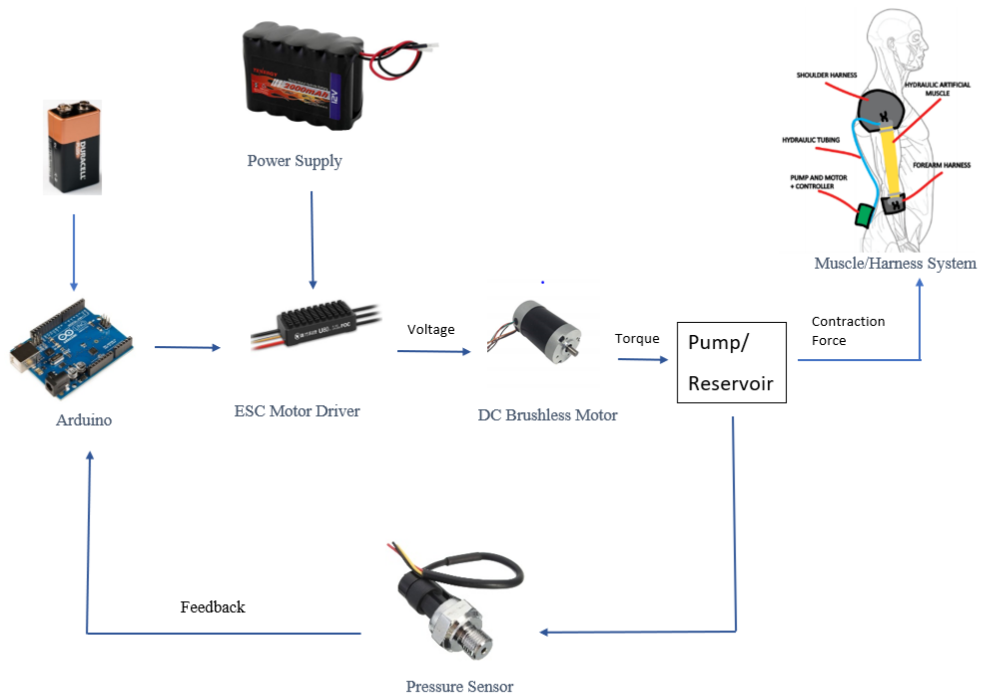



***Fig. 11*** *– Schematic visual of the feedback loop of the main power supply.*

The mentioned components are the essential parts that allow for the pump to work. The pump is responsible for pumping oil into the muscle. The pump uses two gear drivers that forces fluid around the gears which pressurizes the outlet (Figure 12).

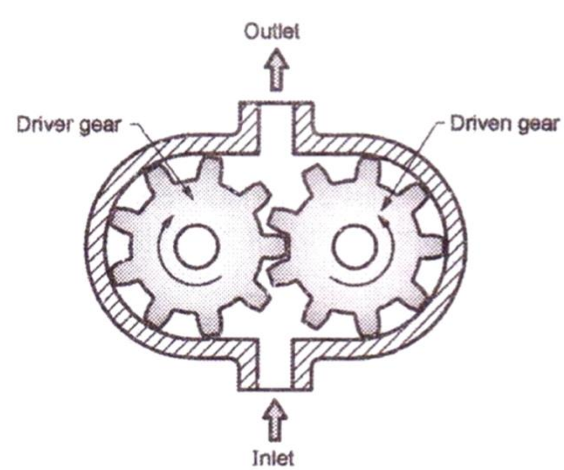
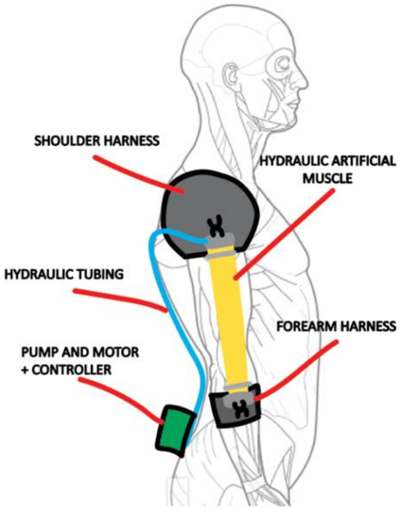


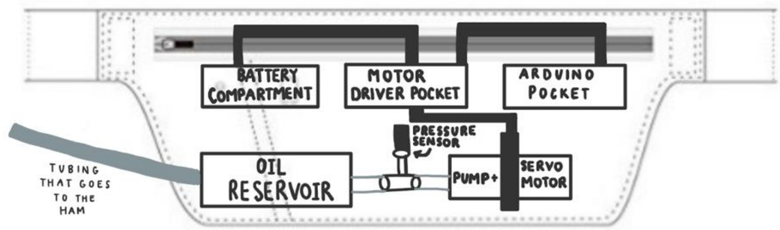

***Fig. 12*** *– Diagram of the two gear drivers present in the pump.*

The set of the components must be a closed loop system, therefore a pressure sensor is connected to the pump and the Arduino. The feedback from the pressure sensor to the Arduino allows the Arduino to regulate the pressure in the pump; which based on testing was found to be between 30 and 40 psi.

The next set of components are the ones that directly affect the user. The hydraulic muscle attached to the shoulder support and forearm strap using D-rings that have been sewn on. The main component in this set, is the muscle. When oil is pumped into the muscle, the muscle contracts; creating rotation in the elbow and lifting the user's arm.

## **Configuration and Parametric Design**




***Figs. 13-14*** *– Final selected design concepts for the exoskeleton and the pumping system pouch.*

Figures 13 and 14 show the final designs for our exoskeleton and pumping system respectively. Due to the soft nature of the materials, we deemed it impractical to make a solid model and felt this illustrated what we were trying to accomplish in a better way. For the exoskeleton itself, we selected flexible materials that would be able to conform to different bodies and be comfortable. This led us to picking a shoulder (Figure 15) and elbow support (Figure 16) to act as the main support system for the exoskeleton.

***Figs. 15-16*** *– Shoulder and elbow supports used for the design.*

It was first discussed to try and manufacture the shoulder and elbow support with the use of a forearm strap. The forearm strap interior has a soft nylon mesh that comes into contact with the skin and an inner neoprene padding for cushioning. In order to fasten the strap to the forearms, a Velcro material was used. Although this set up worked in the beginning, we noticed that after a couple of uses the structure of the strap started to deconstruct and was no longer usable. Therefore, it was easier for these components to be off-the-shelf because they were designed to fit on those body parts. Since, we don't have the understanding of the human anatomy needed to make a support that would provide the support needed and do it safely for the user. Therefore, a well-known brand, such as ACE, would work best since it is an already approved product that helps support/prevent different types of injuries. We were able to also get a hold of some of their products and analyze it in order to see how it affects the movement of the user when it is being used. The cost for this off-the-shelf component is also not expensive and therefore helped keep the cost of our prototype low.

To attach the muscle to the supports, we used steel D-rings (which were sewn on to the supports) and key rings with clasps; this allowed for adjustability and allowed for the muscle to be removed should there be a need for maintenance. The portable pumping system did not need many components, conveniently the system was already made, so our job was to encase it in something that could be worn by the user. Our first thought to accomplish this was to use a "Fanny Pack" again due to its ability to be adjustable and that they are made to fit on a user's lower back comfortably.


***Fig. 17*** *– A suitable "fanny pack" or pouch for the pumping system to be housed in.*

The Arduino and motor driver were to be attached to the walls of the pack using elastic bands, allowing for the system to be removed if needed and to keep them out of the way of the motor and the oil reservoir. We had also planned to attach the oil reservoir and motor to the bottom of the pack using Velcro to keep them from moving around when the user moved. We had also planned to 3D print a box for the motor to be housed in, to prevent any of the wires from getting tangled in it while it was in motion. The pump was to be powered by two 12 volt batteries that were connected in series. This was cheaper than purchasing a 24 volt battery, and they are extremely large and heavy; so they are not practical to be worn by someone. Our design would have been relatively inexpensive, with all of the materials we wanted to purchase, we would have been over $200 under budget; leaving us with ample room should something had gone wrong while creating the prototype.

## Conclusions and Recommendations

To conclude, we believe our design would have been a good stepping off point to having a fully functional exoskeleton. Our design would have accomplished all that was asked of us by our sponsor; which in basic terms was to move the user's arm up and down and be portable. The advantages of our design are that it is adjustable, comfortable and is light weight due to the use of the hydraulic muscle as an actuator and the neoprene supports. The disadvantages are that the pump is rather loud, slow and because we were able to make an initial prototype, we found that the muscle moves the arm, just not as much as we were hoping it would. Where the design can be improved is in the muscle and the pumping system. The muscle only contracts about two inches as it is now, so we believe more research has to be done on materials to see if there is one that gives an even higher contraction ratio. A better pump could also help with achieving the amount of contraction needed to make the full elbow rotation. We are also not sure how the fabrication for the muscle will be proceeded. It would be the most difficult part of the apparatus to manufacture because of the many trials that still need to be done in order to achieve the movement needed. This will also be the most expensive part to manufacture because of the materials needed for the muscle and the oil needed to inflate it. Although this was not the focus of our design, it is still something that needs to be considered for the overall manufacturing procedure and cost. We are disappointed that we did not get to test our design for the portable pump, but this project was very interesting to work on and we are excited to see what kinds of advancements can be made in the future with this technology.

## Acknowledgements

We would like to take this opportunity to thank Professor Hao Su. A lot of the work that we did on the prototype was able to be accomplished because of the access we had to his lab, tools and with the help of the mentors working in his lab. We also would like to thank Michal Walko and Andrés Vélez, who were an integral part in coming up with design concepts and building the prototype.

**References**

[1] NSPE Code of Ethics https://www.nspe.org/sites/default/files/resources/pdfs/Ethics/CodeofEthics/NSPECodeofEthicsforEngineers.pdf

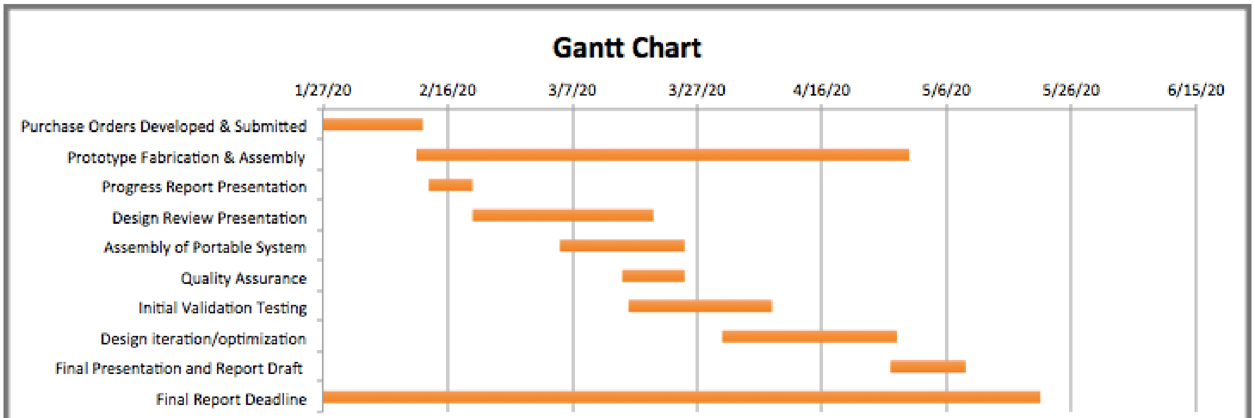
[2] Schulte, H.F. The Characteristics of McKibben Artificial Muscle. 1961.

[3] Su, H. Advanced Mechatronics Lecture 1 and 2 Slides. City College of New York, BIRO Lab. 2019.

[4] Xiloyannis, M. Elbow Exosuit Studies. https://www.michelexiloyannis.com/exosuit

## *Appendix*

### [A] **Gantt Chart ("would be" due dates)**




| | Final Report Deadline | Final Presentation and Report Draft | Design iteration/ optimization | Initial Validation Testing | Quality Assurance | Assembly of Portable System | Design Review Presentation | Progress Report Presentation | Prototype Fabrication & Assembly | Purchase Orders Developed & Submitted |
|---|---|---|---|---|---|---|---|---|---|---|
| Start Date | 1/27/20 | 4/27/20 | 3/31/20 | 3/16/20 | 3/15/20 | 3/5/20 | 2/20/20 | 2/13/20 | 2/11/20 | 1/27/20 |
| Days to Complete | 115 | 12 | 28 | 23 | 10 | 20 | 29 | 7 | 79 | 16 |

### [B] **Code For Hydraulic Artificial Muscle**

HAM_Main

```
/*CREDITS
Arduino Brushless Motor Control by Dejan, https://howtomechatronics.com
Intermediate test program for a thermistor by Limor Fried, Adafruit Industries https://learn.adafruit.com/thermistor/using-a-thermistor
DHT11 thermometer Help - http://www.circuitbasics.com/how-to-set-up-the-dht11-humidity-sensor-on-an-arduino/
*/
#include <Servo.h>
Servo ESC;     // create servo object to control the ESC
int potValue;  // value from the analog pin
int  i=0;

#define DHT11_PIN 7 //thermo                    (do we need this line)[pin 7 is read below but nothing is done with var 'chk']
void setup() {
  // Attach the ESC on pin 9
  ESC.attach(9,1000,2000); // (pin, min pulse width, max pulse width in milliseconds)
  Serial.begin(115200);
ESC.write(0);
delay(1000);
ESC.write(90);

}

void loop() {
int pressurereading = analogRead(A4);
float voltage = pressurereading * (5.0 / 1024.0);
float Pressure = (voltage*150)/4.5;
Serial.println(Pressure);
//Serial.println(analogRead(A5));
//Serial.print("psi");
//Serial.println();
delay(100);
/*


  for(int i=0;i<100;i++)
  {
  if(i==1){ // initializes the motor controller by having a 0 value to the ESC
    // then increases RPM quickly (hence the i=40)
   i=40;
 }

  potValue = map(i*10, 0, 1023, 0, 180);   // scale it to use it with the servo library (value between 0 and 180)

  ESC.write(potValue);    //  the signal to the ESC
        Serial.println(analogRead(A5));
      Serial.println(i);
  delay(4000);
  //Serial.println(potValue);
}
  */

}
```

```
/*CREDITS
Arduino Brushless Motor Control by Dejan, https://howtomechatronics.com
Intermediate test program for a thermistor by Limor Fried, Adafruit Industries https://le
DHT11 thermometer Help - http://www.circuitbasics.com/how-to-set-up-the-dht11-humidity-se
*/
#include <Servo.h>
Servo ESC;     // create servo object to control the ESC
int potValue;  // value from the analog pin
int  i=0;

#define DHT11_PIN 7 //thermo
void setup() {
  // Attach the ESC on pin 9
  ESC.attach(9,1000,2000); // (pin, min pulse width, max pulse width in milliseconds)
  Serial.begin(115200);
ESC.write(0);
delay(1000);
ESC.write(90);

}

void loop() {
int pressurereading = analogRead(A4);
float voltage = pressurereading * (5.0 / 1024.0);
float Pressure = (voltage*150)/4.5;
Serial.println(Pressure);
//Serial.println(analogRead(A5));
//Serial.print("psi");
//Serial.println();
delay(100);
/*


  for(int i=0;i<100;i++)
  {
  if(i==1){ // initializes the motor controller by having a 0 value to the ESC
    // then increases RPM quickly (hence the i=40)
   i=40;
 }

  potValue = map(i*10, 0, 1023, 0, 180);   // scale it to use it with the servo library (value |

  ESC.write(potValue);    //  the signal to the ESC
        Serial.println(analogRead(A5));
      Serial.println(i);
  delay(4000);
  //Serial.println(potValue);
}
  */

}
```