Team Winter Soldier

Preliminary Proposal

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DISCLAIMER

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1 BACKGROUND

1.1 Introduction

The scope of this document is to explain and discuss an arm exoskeleton that will be capable of assisting a person with shoulder and upper arm impairments by allowing them to accomplish tasks throughout everyday life. The ability to complete an overhand pull-up will be used as a benchmarking tool to evaluate the strength of the design. The goal of this project will be to create a successful and lightweight design capable of completing the requirements above. Once this goal has been achieved Professor Lerner and NAU's biomechatronic laboratory plan to further expand on this project, with an end goal to have a wide variety of exoskeleton limbs to aid those in need. In addition to the benefits that the biomechatronic lab will receive, the project's sponsor, W.L. Gore, will be thrilled to see a fully functional system helping those in need.

1.2 Project Description

The following is the original project description provided by the sponsor. "Professor Lerner's NAU Biomechatronics Lab (biomech.nau.edu) develops lightweight wearable robotic exoskeletons to improve the movement of people with walking impairment. In this project, talented students with an interest in robotics/mechatronics will be tasked with creating an arm exoskeleton capable of assisting someone when doing a pull up. The project will involve designing a cable driven actuation system powered by body warn DC motors. Successful completion of this project will lead to a design concept and functional prototype.

This project will have the following deliverables:

- Select appropriate motors and transmission system
- Design and fabricate the body attachment points
- Assemble the arm exoskeleton prototype
- Work with the NAU Biomechatronic lab team to complete pull up tests

Budget: $3,750 (Pending W.L. Gore Approval)."

1.2.1 Original System Structure

Due to the lack of commercial exoskeleton systems, it is difficult to find free research articles. We began our research from a dissertation from ETH Zurich provided by Professor Lerner about the MyoShirt. The MyoShirt is the state-of-art upper arm exoskeleton that this project is based off. It is a compact and lightweight system using cable driven DC motors to power the suit. While the MyoShirt was a phenomenal step in the correct direction, it does leave room for improvement, with the biggest downside being portability. The MyoShirt requires the user to be connected to a station housing all the electrical and computer components sit. A major goal for this team and project is to make a design similar to the MyoShirt but be fully portable allowing the user to roam freely.

As stated before, arm exoskeletons and exoskeleton limbs in general are a very new and niche area of work. With the MyoShirt being an excellent guide and example, the system structure can be broken down in a simple manner. Being constructed of mostly fabric will allow for a comfortable and lightweight design. Due to weight constraints, there will be limited metal components on the system. A sub-system of Bowden cables connected to a small, yet powerful DC motor located on the back, is going to drive the movement of the extremities. To ensure the safe and fluid travel of these cables, a channel allowing for smooth flow without interfering with the user or any other sub-system will need to be implemented.

1.2.2 Original System Operation

Although the human body seems straightforward and simple, it is quite complex and calculating forces as well as determining ‘tendon’ or Bowden cable location will prove to be a challenge. Researchers at ETH Zurich were able to accomplish this task and explained their system as follows: “Forces are generated in a motor unit and transferred to the shoulder via tendons, inducing assistive torques that support shoulder elevation and external rotation. Using motion and force sensors, the user's movements are detected and followed without any additional user inputs” (ETH Zurich). Including the exceptional cable routing that went into the MyoShirt, motion sensors were implemented to detect the movement of the user and then aid them with force in whichever direction was desired. The MyoShirt also supports the users arm against gravity allowing them to be able to move smoothly and effortlessly throughout their daily life.

1.2.3 Original System Performance

The MyoShirt performed exceptionally well in all its tests. The suit was able to increase muscular endurance while holding an object, which can be seen below. Going hand in hand with an increase in muscular endurance, a decrease in muscle activity was also achieved. Having an increase in muscle endurance and a decrease in muscle activity shows the true effectiveness of the system. A concern with an exoskeleton system like one of this nature is that it may restrict the range of motion and flexibility of the user, but the MyoShirt had no effect on any participants range of motion. To power and operate the MyoShirt a sub-system coined, ‘The box,’ needed to be implemented. The box can be seen in the diagram below. A 24V to 5V battery system was used and should supply more than enough power for both the MyoShirt and future designs to come. Issues with this are again portability. The overall goal is to improve on these statistics while also creating a fully portable system (1).

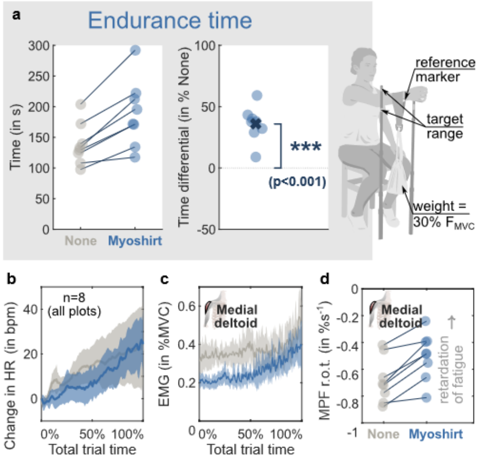


Figure 2: Endurance Time

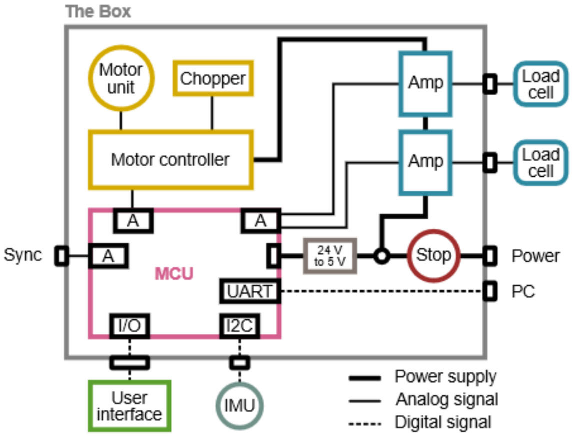


Figure 1: 'The Box'

1.2.4 Original System Deficiencies

Although the MyoShirt is a groundbreaking invention and discovery for the world of exoskeleton design and development, it does fall short in a few distinct areas. Firstly, and most importantly the user is fixed in a radius determined by the cable length attaching them to the batteries. Creating a design that is fully portable but just as strong as the MyoShirt is going to be a challenge but is certainly possible. With the main objective set on creating a fully portable system like that of the MyoShirt, the team set out to accomplish this task.

2 REQUIREMENTS

Dr. Zachary Lerner's NAU Biomechatronic Lab (biomech.nau.edu) develops lightweight wearable robotic exoskeletons to improve the movement of people with walking impairment. For this project the capstone team is assigned to create a shoulder driven exoskeleton capable of assisting someone when doing a pull up. The exoskeleton will provide support to both shoulder joints and will aid in overhead pushing and pulling movements. This device needs to use a cable driven system powered by body warn DC motors used in Dr. Lerner's other projects. Additionally, the team discussed a possible collaboration with some of Dr. Lerner's students who are developing an elbow joint exoskeleton. We aim to create a design that can complement his other projects and create a strong base for future research.

2.1 Customer Requirements (CRs)

Given the requirements listed above, the capstone team and Dr. Lerner came up with multiple customer requirements to begin our design process.

1. Safety
2. Comfort
3. Portable
4. Stability
5. Low profile
6. Lightweight

The two highest rated customer requirements are a lightweight system, and a low profile. Dr. Lerner commented during team meetings that the device should not be limiting any range of motion or weighing down the person. Instead, he wants a design that sits close to the body and is made from lightweight materials. The team decided the best way to approach these requirements is by 3-D printing our larger components to reduce weight.

The second highest rated customer requirements are stability and safety. These requirements are complementary, as a stable system will reduce the risk of injury to the user. The shoulder is a complex unit, controlled by the glenohumeral and clavicular joint. The designs will have multiple anchor points to secure these joints and implement a few mechanical fail-safes to shut down the device if needed. By making safety and stability a priority, we recognize the potential dangers of our design and improve them to make it as secure as possible.

The lowest rated customer requirements are portability and comfort. These requirements may be scored lower; however, they are still very important to the design process and selection. Portability was chosen as a customer requirement because Dr. Lerner wanted to avoid the MyoShirt's dependency on an external control system. The exoskeleton needs to have motors, battery, and wiring all mounted to the body. Comfort is also an important requirement, however Dr. Lerner mentioned he is willing to sacrifice a little bit of comfort to increase mechanical assistance. The design will make sure to keep all the wiring off the body, to avoid abrasion and irritation of the skin.

2.2 Engineering Requirements (ERs)

The engineering requirements are based off the customer requirements provided by Dr. Lerner. These requirements are goals that the team must aim for the design to be successful.

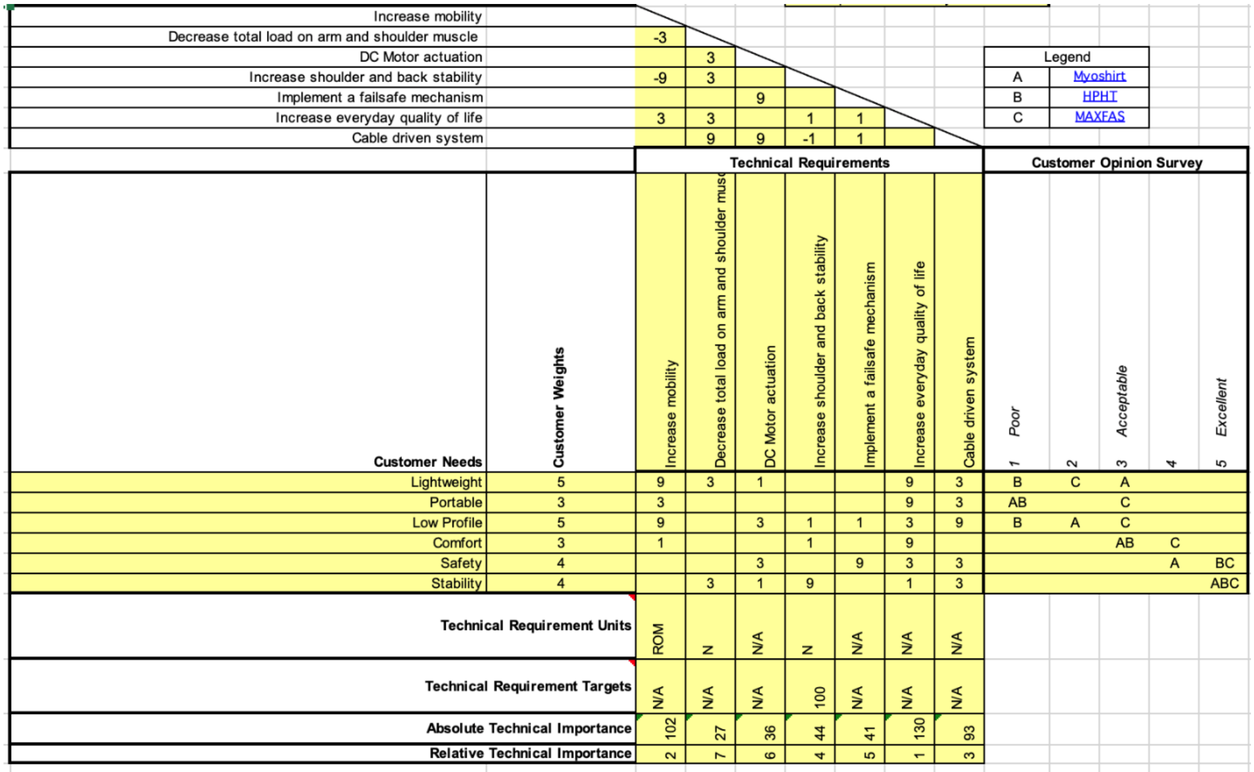
1. Implement a DC (direct current) motor to aid the pull-up.
2. Implement a cable driven system.

3. The entire exoskeleton must be less than 6lbs.
4. Components of the design cannot protrude more than 10cm from the body.
5. The exoskeleton must provide around 15-20% assisted force.

The first two engineering requirements are the required materials we must use in the design. The Biomechatronic lab uses AK Series Dynamic Modular motors that are specifically designed for use in exoskeleton designs. To assist the lab in their research, the team will be using the same type of motors. This will allow future teams to build upon the design, as they are already familiar with the type of motors, the team is using to power the exoskeleton. Similarly, Dr. Lerner wants to implement a cable driven system to provide power and support to the shoulders.

The last three engineering requirements focus on the mechanical properties of the exoskeleton and set realistic quantitative goals for our design. The weight and protrusion of the system must stay below the required limit to meet the customer requirements of lightweight and portability. The reason behind this is to have a design that can be worn in everyday tasks. Eventually, a design with assisted shoulder movement can be used by warehouse workers, construction workers, and other jobs that require continuous lifting and pulling movements throughout the day. This design needs to be able to handle repeated loads over time, which is why the initial assisted force is set at a lower goal. Fifteen to twenty percent assisted force will be measured in our second semester of testing and may be modified to provide more assistance if the design is successful.

2.3 House of Quality (HoQ)



	Increase mobility	Decrease total load on arm and shoulder musc	DC Motor actuation	Increase shoulder and back stability	Implement a failsafe mechanism	Increase everyday quality of life
Increase mobility						
Decrease total load on arm and shoulder muscle	-3					
DC Motor actuation		3				
Increase shoulder and back stability	-9	3				
Implement a failsafe mechanism			9			
Increase everyday quality of life	3	3		1	1	
Cable driven system		9	9	-1	1	

Legend	
A	Myoshirt
B	HPHT
C	MAXFAS

		Technical Requirements							Customer Opinion Survey				
Customer Needs	Customer Weights	Increase mobility	Decrease total load on arm and shoulder musc	DC Motor actuation	Increase shoulder and back stability	Implement a failsafe mechanism	Increase everyday quality of life	Cable driven system	1 *Poor*	2	3 *Acceptable*	4	5 *Excellent*
Lightweight	5	9	3	1			9	3	B	C	A		
Portable	3	3					9	3	AB		C		
Low Profile	5	9		3	1	1	3	9	B	A	C		
Comfort	3	1			1		9				AB	C	
Safety	4			3		9	3	3				A	BC
Stability	4		3	1	9		1	3					ABC
Technical Requirement Units		ROM	N	N/A	N	N/A	N/A	N/A					
Technical Requirement Targets		N/A	N/A	N/A	100	N/A	N/A	N/A					
Absolute Technical Importance		102	27	36	44	41	130	93					
Relative Technical Importance		2	7	6	4	5	1	3					

Figure 3: House of Quality

The team created a house of quality to show how our customer requirements relate to our technical requirements. A HoQ is a powerful tool used in the early stages of the design process to organize and prioritize certain functions to meet the demands of the customer. The team met to score each section as either a 9, 3, 1, or 0 to rank its importance. From an initial analysis they found that the design must primarily focus on decreasing the load directly onto the shoulder joint. Additionally, the use and understanding of the type of DC motor the design will be using will be crucial to the design process. After the HoQ meeting, the team made sure to research the technical aspects and connection points of the motor, to incorporate them in their concept generation. Additionally, the team agreed that a mechanical failsafe will be crucial to each design, as the shoulder can be a delicate joint. The team discussed multiple different failsafe's, such as locking systems, limiters, and kill switches to make sure the design is as safe as possible. Stability of the shoulder was another focus and will be key for the success of the exoskeleton design. This ties into the use of a cable driven system, as anchor points will be needed to secure the cable as well as provide points of stability. Due to the generation of the house of quality occurring before the teams visit to the biomechatronic lab, they were not as focused on everyday quality of life and mobility. However, after meeting with Dr. Lerner, he explained that he wants full upward and downward mobility and gave specific movements to focus on assisting. The design is no longer completely focused on everyday quality of life, but instead focused on assisting tension and compression of the shoulder joint. The house of quality gave guidance and support for the next stage of the design process, literature review and benchmarking.

3 DESIGN SPACE RESEARCH

The following chapter includes the literature review, benchmarking, and functional decomposition for the project. Each of these topics will be discussed in greater detail in the following sections below.

3.1 Literature Review

When researching exoskeleton and specifically upper arm exoskeleton systems not a lot of information is out there because the field is still developing and is very new. Although hundreds of sources are not yet available, the team was successful in finding sources useful in benchmarking and design research. Since there are many components that go into design and creating an exoskeleton system of this caliber, the team decided that it was best to spilt up the literature review research into subsystems and below are the sources that each team member found, and the reasoning behind including the source into any design conversation.

3.1.1 Student 1 (Colin Cipolla) – Motor Comparison for Use in Exomuscle

The motor selection for the use in the project is one of the most important aspects. Making sure the team choose the right motor is vital for the success of the project. This literature review is going to look at the best motors currently available and determine which one is most suitable for the designs application.

The first motor is from a company called T-Motor. This motor is the AK60-6 V1.1. The motor weighs 368g which is perfect for the design as the team is trying to reduce the weight of the design as much as possible. The motor's height is 39.5mm which meets the requirements given by the client as to not protrude more than 10cm from the body. This motor is 80KV which means 80 rpm (revolutions per minute) per volt supplied to the motor. This allows the team to determine the speed at which the motor operates by choosing the voltage to put into the motor (33).

The next motor is from a company called CubeMars Motion Advanced Robotic System. This motor is another motor specifically designed for use in exoskeletons which is perfect for technical applications. The motor is called the AK10-9 KV100. This means that the motor operates at 100KV which allows the user to choose the speed and torque always coming from the motor. The motor weighs 820g which is just under 2 pounds meaning that they are heavy for the teams design. The advantage to this motor is the rated torque of 18 N-m which is much higher than the previous motor rated at 3 N-m. The increased torque rating means the team may be able to reduce the number of motors required while offer ingthe same performance (34).

The third motor is from Genesis Robotics & Motion Technologies. The model number being 095-012-BNA. This motor is 930g meaning it is heavier than the one previously discussed. The outer diameter of this motor is 95mm making it large. The downside to this motor is its size combined with the lack of torque output. The rated torque of this motor is 2.53N-m making it the largest and weakest motor so far. Based on the statistics given by Genesis Robotics this motor will not suit the requirements and the team should look for better motors on the market (35, 33).

The next motor is from Techsoft Robots. This motor is called the 6425 motor and has a rated voltage of 48V. The motor weighs 510g which makes it viable for use in a lightweight design. The rated torque is 2.8N-m which is slightly lower than the third motor, but it is almost twice the weight meaning there may be a better motor for the application (35, 36).

The last motor is a different model from T-Motor. This is called the AK70-10. This is a 100KV motor that weighs 521g making it usable for lightweight application. The rated torque is 8.3N-m meaning it has plenty of power for the application that it will be needed in and may be able to reduce the total number of motors needed for the design. The motor has an outer diameter of 89mm and a height of 50.25mm making it a good choice for meeting the clients' requirements (37).

Overall, the motor that will fit the specific application the best is the first motor discussed while offering 3N-m of torque with a weight of 368g. The other motors are great for this application; however, some do not meet all the requirements needed (33).

3.1.2 Student 2 (Dylan Kurz) - Shoulder, Back and Arm Anatomy

When conducting research for the arm exoskeleton the team decided to split up the major topics into smaller sections that each team member could research and find adequate resources on. Dylan was instructed to conduct research on the anatomy of the arm, shoulder, and back muscles. Going into detail on how each muscle contracts, operates, and functions with one another.

(1) Reference 1 - The Anatomy of the Latissimus Dorsi Muscle:

The Latissimus Dorsi or more commonly known as the lats, are a large muscle group located in the mid back. The lats originate from the bottom six thoracic vertebrae and is inserted all the way up to the bottom of the shoulder blade. A diagram of the lats location and insertion points will be provided below.

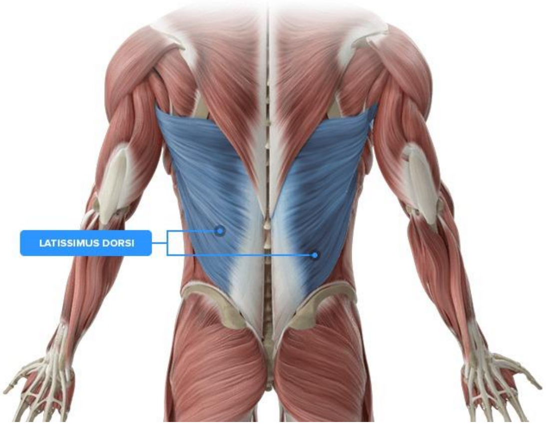


Figure 4: Diagram of the Latissimus Dorsi

The main function of the lats is to pull the elbow down towards the hip. In real world applications the lats main goal is to pull the body up. Good examples of the lats activating are doing exercises such as pull-ups, rock climbing and even swimming (18).

This reference is going to prove to be crucial for the team when designing their exoskeleton. The main purpose of the lats is to pull the body up, and the main benchmarking test for the team is to see the strength increases when completing pull-ups. Having a good and solid understanding of the function and purpose of the lats will prove to be vital (18).

(2) Reference 2 - The Anatomy of the Shoulder:

Being a ball and socket joint, the shoulder is very complex but can be broken down into two joints. The first being the acromioclavicular joint which connects the scapula (shoulder blade) and the clavicle (collar bone). The second being the glenohumeral joint which is where the ‘ball’ or humeral head meets with the ‘socket’ or glenoid. The rotator cuff connects joints listed to the muscles via tendons. Tendons are what attach the muscles of the shoulder to the bone (19).

The mobility of the shoulder is very vast. Knowing the anatomy of the shoulder and where the tendons lie along the structure will prove to be very useful when determining where the cables of the exoskeleton should run because having them run with the existing tendons will be far more effective and efficient. A diagram showcasing the tendons within the shoulder will be provided below.

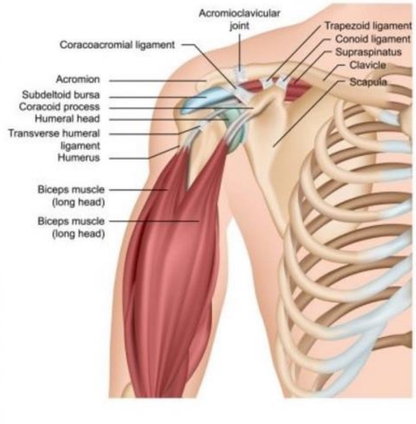


Figure 5: Diagram of the Shoulder

(3) Reference 3 - Anatomy, Shoulder and Upper Limb, Biceps Muscle:

The biceps brachii is composed of two different heads, the short head (caput breve) and the long head (caput longum). The long head of the bicep originates from the supraglenoid tubercle and superior glenoid labrum, while the short head starts at the elbow and meets up with the long head and transitions into the shoulder (21). The anatomy of the bicep will be showcased in a visual manner below.

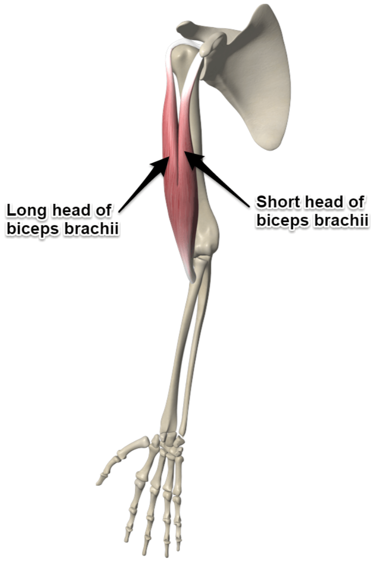


Figure 6: Diagram of the Bicep

The primary focus of the biceps are elbow flexion and forearm supination. The biceps are the other primary activator when performing a pull-up next to the Latissimus Dorsi. The bicep is a simple muscle but is a main contributor to the work that the team is trying to accomplish. Inserting an anchor point at the connection point between the bicep and the elbow and running a cable along the bicep, acting like an artificial muscle will prove to be a major component in the exoskeleton designs to come.

(4) Reference 4 - Anatomy, Back, Trapezius:

Although the Latissimus Dorsi is the primary back muscle involved when performing any kind of pulling motion such as a pull-up, it is not the only contributor when it comes to back muscles. The Trapezius or commonly known as the traps, are large back muscles covering much of the upper back and aid in the pull-up motion. The traps extend from the external protuberance of the occipital bone to the lower vertebrae. There are a total of three different groups of traps, the upper, middle, and lower groups.

Upper Traps - The upper traps help with the upward rotation of the scapula and provide additional shoulder stability (20).

Middle Traps - The middle traps are responsible for aiding in shoulder retraction and rear arm extension. They also provide additional shoulder stability while the arms are moving (20).

Lower Traps - The lower trap helps to depress the scapula, as well as help the upper fibers of the trapezius upwardly rotate the scapula (20).

When discussing the action of a pull-up the main thing that the traps allow for is the decompression and retraction of the scapula. By retracting the scapula, the lats will inevitably have a better range of motion making it much easier to pull the elbow towards the hip. The traps will also internally rotate the arms allowing for a better setup for any pulling actions. Knowing all this information the team can better mount the motors and cable system to allow for scapula decompression and retraction. Below is a visual representation of the traps.

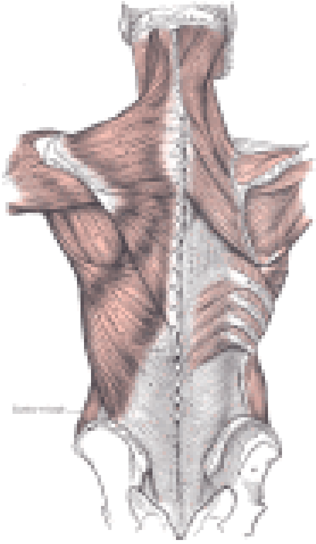


Figure 7: Diagram of the Trapezius

(5) Reference 5 - Muscles Used Within a Pull Up:

The pull-up, although a simple exercise, uses a vast number of different muscles within the body to complete the task. Below is a figure depicting the primary and secondary muscles used in the pull-up. The muscles that are mainly used throughout the pull-up motion are as follows: the Latissimus Dorsi, the Teres Major, the Trapezius, the Pectoralis Major, the Rhomboids, the Biceps, the Upper back, the forearms, and the abdominals (22).

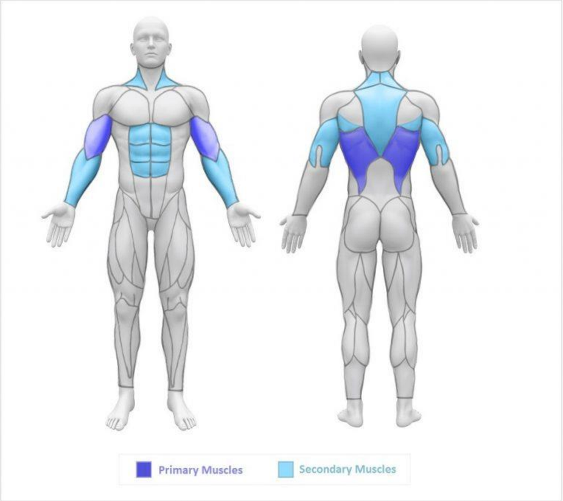


Figure 8: Diagram Showcasing Primary & Secondary Muscles

Although the team will not be accounting for all the different muscles involved in a pull-up, it is still a vital thing to know what muscles are being used because it will give the team a better understanding of the movement to allow them to create the most effective design possible.

3.1.3 Student 3 (Jordan Finger) Material Properties and Behaviors

References 38 through 42

Within the limited scope of this project the next area of research necessary for the team is the background of the material that will be used for components of the exoskeleton and cable system. Jordan was tasked with this area of research to find detailed information on the materials, properties, or characteristics they may exhibit that will be important to the team when the time comes to prototype and fabricate models of the exoskeleton.

The team plans to use a 3D printing filament called Onyx. The filament itself is known to be very strong and flexible. But there are ways to increase the performance of 3D filaments, and this is usually done through the printing process. It was found in this case study that printing the infill at a 0-degree angle produced a greater strength for the PLA than compared to the 90-degree infill angle that is more standard. Another study found that printing beams in the upright position had a 50% reduction in strength than if they were to be printed flat. Other conditions that were tested in the case study were parameter properties, material properties, and printer properties.

From the parameter properties, the filament was printed in different humidity conditions. In Figure 9, Wet refers to samples conditioned in water for 14 days. Cond. Is for samples conditioned at 44h at 52% RH. Lastly Dry is the sample conditioned for 14 days in a sealed container.

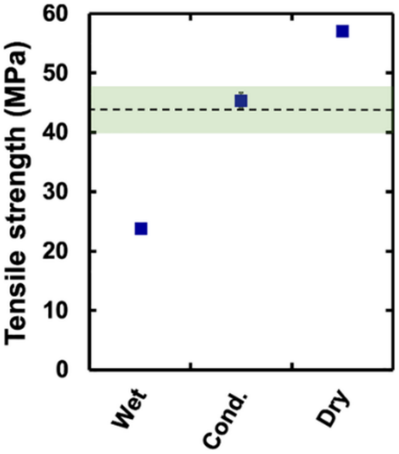


Figure 9: Material Parameter Test Results

The second 3D print filament to be used for this project is carbon fiber. Like Onyx it is strong, flexible, and durable. Similar results were found in this study on carbon fiber PLA that displayed increases in strength of the filament when the printing process was changed. The study found that reinforcing PLA composites with carbon fiber had increased the tensile strength and other properties of the filaments. “The storage modulus of the modified carbon fiber reinforced samples was about 166% and 351% higher than the PLA and PLA with neat fibers, respectively.” (396). There are properties that increase the strength of the filaments but there are also properties that can decrease the strength and be less beneficial for its use. The study found that the nominal print head temperature is between 200-230 degrees Celsius, but the thickness of the print is where the strength decreases by nearly 60% for thicknesses of 8mm. A thickness range of 1.8mm to .4mm increased the flexural strength from 130MPa to 335MPa (396).

Neoprene is a material that is commonly used in rehabilitating applications, injury stability applications, and athletic applications. Things such as knee braces, posture correctors, compression sleeves, etc. What makes fabrics such as Neoprene popular are their fiber properties and composition. Woven, braided, and stitched fibers contain different properties that allow them to strain, deform, and be elastic compared to others that don’t exhibit these properties. Typical rubber has a stiffness of 1 Nm m^-2 which is very low for a material. Neoprene is a synthetic rubber that has a strain break of up to 625%. This material is also reliably resistant to any weathering effects from the sun and environment while still being durable from a temperature range of -25 to 93 degrees Celsius.

Fibers have two different characteristics to them: Warp and Weft fibers. Test subjects loaded parallel in the warp direction fail in a brittle manner. For subjects loaded parallel in the weft direction they fail by breaking the fibers within and permanently deforming the rest of the subject.

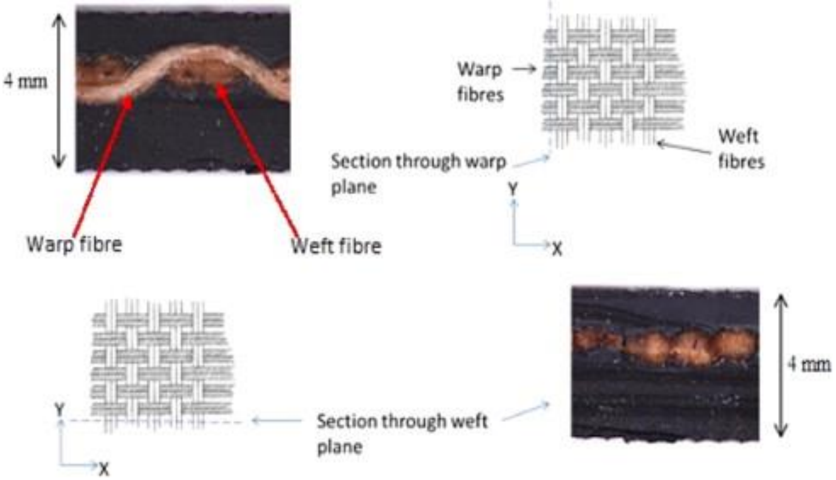


Figure 10: Warp and Weft Fibers

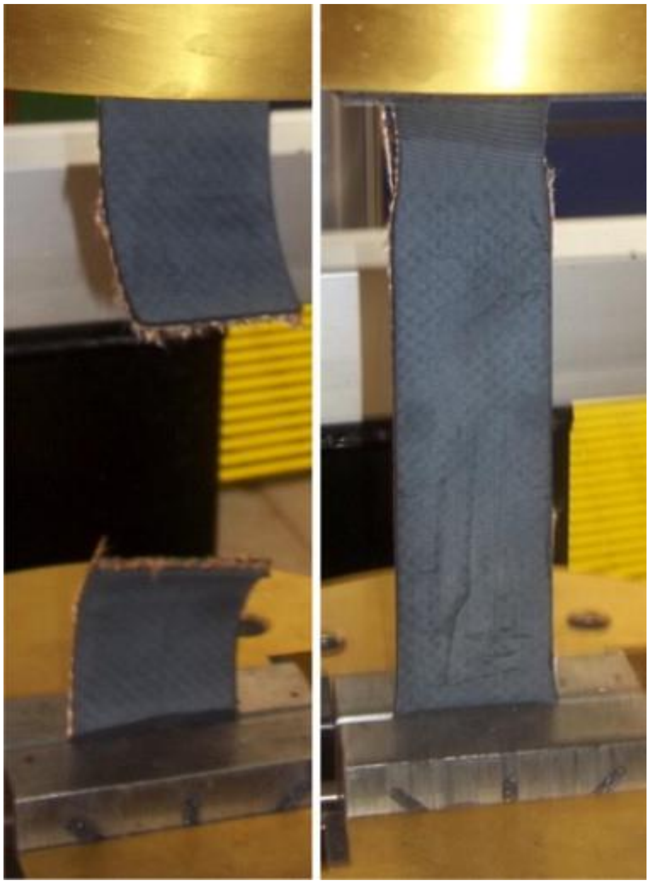


Figure 11: Warp and Weft Loading Failures

The image above shows the warp loading on the left and the weft loading on the right and how these materials failed. Neoprene is a considerable option for this project for any wearable materials due to its ability to stretch largely before strain and deformation.

Medical grade filaments are a market segment that is severely lacking in the industry currently. There is a lack of materials that meet the specific requirements necessary to operate and use in modern medication. The thermal properties, cost, reliability, mechanical properties, and more are all areas that require an in-depth amount of consideration. FDM/FFF is a medical grade filament under the name

Bioflex. Bioflex is one of the only widely used medical grade filament which begs the attention to be directed towards finding other filaments that meet these medical grade requirements. Bioflex is of the thermoplastic elastomers group (TPC). A slightly different and unique variation to the widely accepted PLA filament and modifications applied to them. This filament has potential in medical devices and long-term bone implants. Although the scope of this exoskeleton project pertains to the medical section of rehabilitation, working with a material such as Bioflex to incorporate into the designs could be promising for it being a highly important medically recognized filament that can be used in intricate operations.

3.1.4 Student 4 (Michael George): Transferring of Force Using Bowden Cables and Muscular Exertion within the Arm

Within everyday life the arm and movement are essential to what can be accomplished, within different lines of work there may be a necessity that one must have and be able to use one's shoulder in its full range of motion. In studies conducting tests of weight and non-weighted arm raises symptoms 24 hours after the fact were mostly located in the lower trapezius (28). Rather than try to mimic the complex movement of the shoulder and the arm in a rigid exoskeleton, use flexible but non-elastic Bowden cable for force transferring. Effectively cutting down on weight and non-linearity to achieve a more efficient transfer of force around the curves of the geometry of the body (29). The ability to move a force around a 3-dimensional body allows for the precise placement and directional force application needed to properly assist the motion of the shoulder.

Though Bowden cables provide a flexible form of force transmission, the efficiency of such transmission is affected inversely with the angle of bend within the cable itself. This relationship can be seen through the capstan equation $\mathrm{Ft,o} = \mathrm{Ft,i} \cdot \exp(-\mu \cdot \sigma)$. Using this and a combination of cleverly placed sensors an overall output force can be determined from the actuation unit itself. This can be accomplished by measuring the reaction force on the sheath of the Bowden cable and the current bend within the cable can be measured using a Hall effect sensor and magnet as shown with Figure 9 (30).

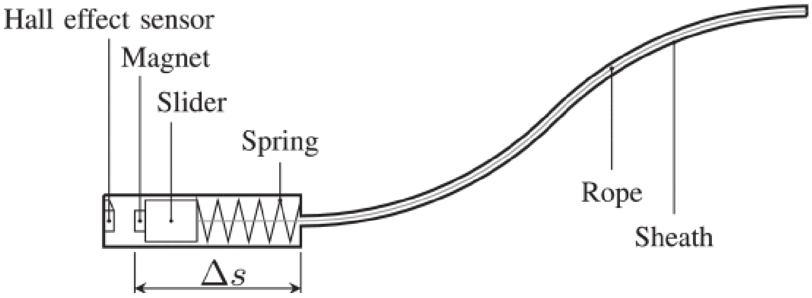


Figure 12: Bowden Cable Sheath

Bowden cables in the applications of assisting in industrial work is a prime location for a shoulder assistance system as having a device to reduce the muscular activation can be an indication of a reduced risk of injury, by compression of tendons and lack of circulation (31). Though the total force of working and potential carrying and or holding an object above one's head is not offloaded from the musculoskeletal structure it is effectively repositioned to a different more stable area of the body. With the proper position of Bowden cables around the body the weight of one's arms and any object which one may be carrying can effectively be moved to a stronger muscle. With the help of optimizing force outputs the total exertion can be reduced to almost zero (30).

3.1.5 Student 5 (Michael Marchica): Force Coupling in the Shoulder and Scapular

Rhythm

The shoulder is one of the most complex regions of the body, with multiple joints and muscles working simultaneously to create stability. The three main bones in the shoulder are the clavicle, sternum, and scapula (25). The shoulder complex is composed of 3 physiological joints and one floating joint: the glenohumeral (GH), acromioclavicular (AC, sternoclavicular (SC), and scapulothoracic joint (ST) (25).

A force coupling is a term used in statics to describe a system with two equal and opposite forces that induce a moment with no net force (21). An example of a force couple could be a lug wrench that induces a moment onto a bolt of a wheel cap without exerting a force into the wheel itself. These moments create rotational energy without translation of the joint (22). The main difference between a couple moment and regular moment is that the magnitude of the moment due to a couple will always be equal to the magnitude of the forces times the perpendicular distance between the two forces (22)

In the human body, two or more muscles in the shoulder create opposing forces to provide stability to the joint and allow movement of the arm. The three main force couples that help move and control our shoulders are the deltoid-rotator cuff, upper trapezius, and serratus anterior, and the anterior-posterior rotator cuff.

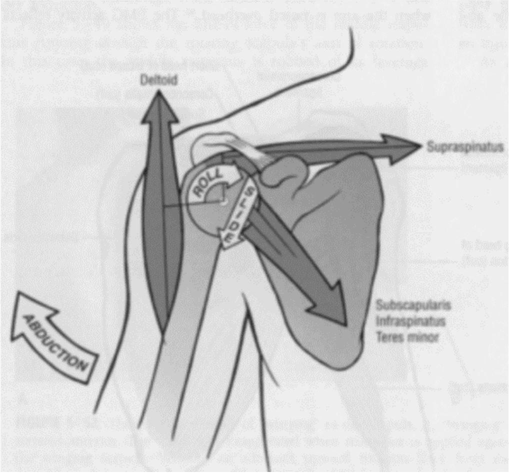


Figure 13: Deltoid-rotator cuff force couple (23)

The deltoid-rotator cuff force couple provides the largest amount of force out of the other three couples. As seen in the figure above, when raising the arm overhead, the deltoid will cause an upward and outward force on the humerus during its first part of motion. As the humerus is rases, three rotator cuff muscles will create a downward and inward force on the humerus to keep the ball joint of the shoulder in its socket (23). To maintain proper positioning of the humerus, the supraspinatus will assist in creating a compressive force to balance the rest of the forces (23).

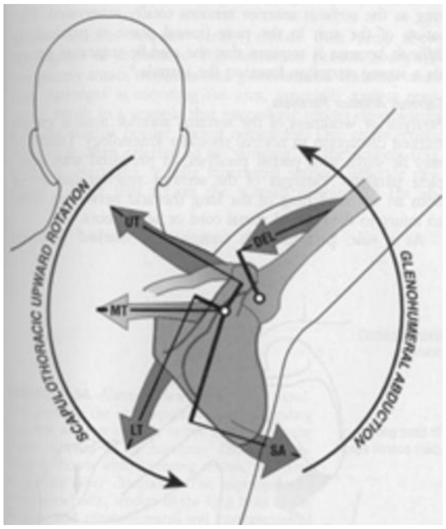


Figure 14: Upper trapezius and serratus anterior force couple (23)

The upper trapezius and serratus anterior force couple is used to produce an upward rotation of the scapula (shoulder blade) when raising our arms. This joint is more complicated and is supported by four major muscles: the serratus anterior, lower trapezius, upper trapezius, and levator scapula. As shown in the figure above, these muscles each act in a different direction on the scapula, which allows for upper rotation of the shoulder blade while keeping the glenoid (shoulder socket) in proper positioning (23). To maintain shoulder stability when raising the arm to the side, the serratus anterior and lower trapezius act as the primary stabilizers (23).

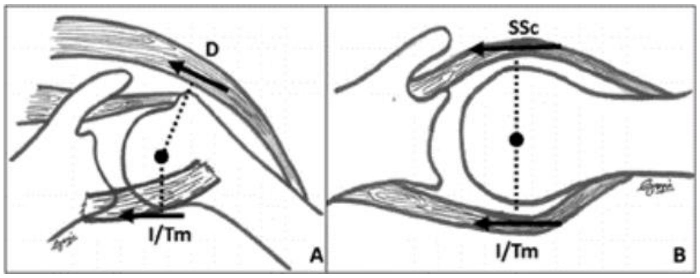
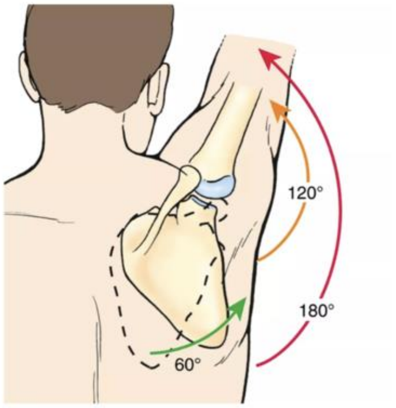


Figure 15: Anterior-posterior rotator cuff (23)

The anterior-posterior rotator cuff is made up of the subscapularis (front), and infraspinatus and teres minor (back). This rotator cuff creates a downward stability within the shoulder to maintain the humeral head within the socket when elevating the arm (23). As seen in the figure above, the infraspinatus and subscapularis pull downward and inward at a 45-degree angle, while the teres minor pulls downward and inward at about 55 degrees to keep the shoulder centered on the joint (23).



(C) Scapulo-humeral rhythm. The scapula and humerus move in 1:2 ratio. When the arm is abducted 180 degrees, 60 degrees occurs by rotation of the scapula, and 120 degrees by rotation of the humerus at the shoulder joint.

Figure 16: Scapular-Humeral Rhythm (24)

Another way we can break down and analyze the movement of the shoulder is by assessing its scapulohumeral rhythm, which defines the kinematic interaction between the scapula and the humerus (24). This rhythm dictates the timing of movement at these two joints during shoulder elevation and is broken into multiple phases. The first "setting" phase is the 0–30-degree range of motion and is dominated by the glenohumeral joint. After the setting phase the glenohumeral and scapulothoracic joints will move simultaneously, at a respective ratio of 2:1 (24). This ratio can be calculated by dividing the total amount of shoulder elevation (humerothoratic) by the scapular upward rotation (scapulothoracic) (24). If the scapular rhythm is out of balance, we know that there is a change of normal position of the scapula related to the humerus.

(6) Reference 1 – Force Coupling Mechanics
(7) Reference 2 – Shoulder Biomechanics and Exercises
(8) Reference 3 -The Importance of Force Couples in the Shoulder
(9) Reference 4 – Scapulohumeral rhythm
(10) Reference 5 – Biomechanics of the Shoulder

3.2 Benchmarking

Benchmarking is the process of measuring the performance of different companies' products, and in the case of this report, benchmarking was used to compare the various state-of-the-art exoskeleton systems specifically designed for shoulder improvement. The team was given a dissertation provided by Dr. Lerner at the beginning of the project about the MyoShirt, saying this is what he wanted to improve upon. With a baseline in mind, the team was able to expand on this idea and research a few more designs that were like the MyoShirt but different enough to provide the team with new ideas and options. The biggest improvement that the team and Dr. Lerner wanted to make was to create a version of the MyoShirt that was fully potable, slim, and lightweight to truly aid those who need it in everyday life.

3.2.1 System Level Benchmarking

After conducting research on the state-of-the-art versions of an upper arm exoskeleton, the team decided on a top three to compare in their benchmarking tests. The reason behind choosing the designs below was because they best fulfilled the customer and engineering requirements that were described earlier in the report. The three existing designs and their various subsystems will be discussed in far greater detail in the sections below.

3.2.1.1 Existing Design #1: ETH Zurich's MyoShirt.

The MyoShirt is the current state-of-the-art model that the team wishes to replicate and improve upon. The system involves a soft wearable robotic suit that assists the user with upper limb use in daily life. The goal of the MyoShirt was to improve the mobility of the shoulder for those that have shoulder impairments. The suit is a textile-based assistive device, meaning that it can be worn without any changes to the user's outfit. The bulk of the weight from the MyoShirt including the motors and batteries are located off the shirt and are in something coined 'the box,' which is off to the side of the user. Additionally, the MyoShirt can sense the users' movements and can respond intuitively by assisting the user in whatever direction they were trying to move in. Lastly, the MyoShirt aids the user with heaps of shoulder stabilization. The shirt resists the effects of gravity and having only one motor per arm, the suit can support many multiarticular movements such as reaching and grabbing (1).

The MyoShirt relates to the customer requirements tremendously. First off, the MyoShirt is super lightweight, which is one of the main requirements for the team. Going off the lightweight feature of the MyoShirt, it is also very slim and does not protrude far off the user. On top of this, the MyoShirt is a cable-driven system using Bowden cables, which is another requirement for this project. Lastly, the MyoShirt provides extra stabilization to the shoulder joint, which is something the team is striving towards. Below is a photograph of the MyoShirt (1).

Figure 17: MyoShirt

3.2.1.2 Existing Design #2: CAREX; A cable-driven arm exoskeleton for neural rehabilitation.

Like the MyoShirt the CAREX exoskeleton is an upper arm cable-driven system that aims to aid in shoulder rehabilitation and stabilization. The CAREX exoskeleton also uses a battery and motor system located off the user, but instead of having a box hold all the electronics off to the side, the CAREX uses a system of tracks located on the ceiling. This system allows the user to move around without having the feeling of a cable dragging behind them. Although a very good idea it is not something that the team wishes to improve upon (4).

The thing that separates the CAREX suit from the MyoShirt is that it does not use a fabric system but rather a cuffing system at each of the major joints in the arm (i.e., the shoulder, elbow, and wrist). The team really liked this idea of a cuffing system and would like to implement it and the use of fabric into their final design. The idea of implementing a soft fabric-like cuff that sits just above the elbow is something that the team is looking to implement. Below is an image depicting the cuffing described above (4).

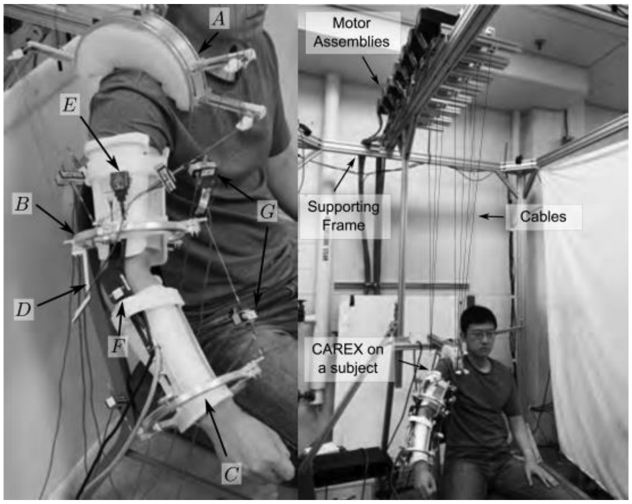


Figure 18: CAREX Cuff System

3.2.1.3 Existing Design #3: SAM: A 7-DOF portable arm exoskeleton with local joint control

The SAM or Sensoric Arm Master is a fully portable exoskeleton with actuation and sensors to help aid in the user's movement. The SAM has integrated local joint control, meaning each cuff or joint has its own motor coupled with a sable capstan and gearbox. This design helps improve the overall performance of the device, but at the cost of weight gain. The goal for the team is to have a system that weighs less than six pounds and the SAM device comes with a total weight of 13.23lbs. On top of this increase in weight, most of the mass is located at the shoulder, specifically around 65% of the total weight. While the SAM is the first fully portable device looked at by the team, the additional stress that the additional weight will cause to the user is something that the team is not interested in. With all that being said, the SAM does provide the team with some insight on how to make a fully portable device. (32). Below is a diagram showcasing a model of the SAM.

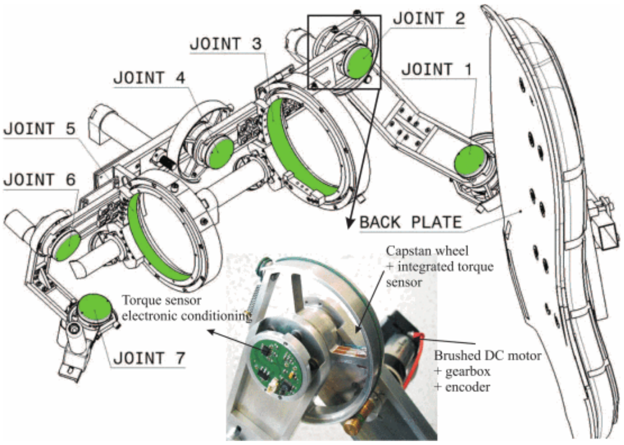


Figure 19: Sensoric Arm Master

3.2.2 Subsystem Level Benchmarking

Arm exoskeletons are a complex thing and the design that the team is striving for is no exception. To make things much easier to understand and interpret, the team has decided to break up the main system into three separate subassemblies, which are as follows: the motor location and mounting, the cable routing, and the anchor points along the arm. Each subsystem will be discussed in greater detail below.

3.2.2.1 Subsystem #1: Motor Location and Mounting

The location of the motor assembly is going to prove to be crucial for the overall effectiveness of the design. Having a motor location that is either too low on the back or too high may cause cable routing issues, safety concerns or comfortability issues. Going off where the motors will sit, it is just as important that the way the motors are mounted is just as important. The team is striving to create an exoskeleton that not only works but also is fully portable and slim, so having motors lay flush and comfortably along the body is critical. Below the motor location and mounting process for each existing design will be discussed below.

3.2.2.1.1 Existing Design #1: MyoShirt

The box that the MyoShirt uses is where all the motor and electrical components sit, therefore the shirt is so lightweight and comfortable to wear. The box is not something that the team wants to pursue when determining the motor mounts and location because it goes against the portability requirement for the design.

3.2.2.1.2 Existing Design #2: CAREX

Like the MyoShirt the CAREX uses a motor assembly that sits above the user along a track. While more portable than the MyoShirt, the team still does not want to pursue this idea for the motor mounts and location. The location for the motors is just not what the team had in mind and does not provide that much additional information and aid to the team and their requirements and goals.

3.2.2.1.3 Existing Design #3: SAM Exoskeleton

The SAM is the only existing design that is fully portable so the way that the motors are mounted, and their location was very intriguing to the team. After careful inspection and consideration, the team does want to move forward with this idea but wants to make some changes to it to better fit their goals, requirements, and design specifications. While this SAM system does meet the team's requirement of being fully portable, it does not meet the requirement of being slim and not protruding more than ten centimeters off the body. To improve the design to better meet the team's needs, instead of attaching the motors at each joint, the team wants to run cables from the elbow and shoulder joints down the back to the low back where the motors and electrical components will be stored.

3.2.2.2 Subsystem #2: Cable Routing

Having simple yet effective cable routing is critical for overall success. The cables that attach the motor to the actual arm need to be routed in such a manner that it is safe for the user, and it allows for a full range of motion. The cables need to be routed so they help the operator's movement and do not hinder it. The best way to accomplish this task is to go simpler rather than more complex. The team is striving to use just one cable system per arm. This will allow for the most natural movement possible without 'over-doing,' it. Below are a few existing designs that route their cables in such a way that is explained above.

3.2.2.2.1 Existing Design #1: MyoShirt

The MyoShirt is extremely sleek and slim, there is almost no protrusion coming off the body. The issue arises with the MyoShirt when you zoom out and see the box. The user of the MyoShirt is basically hardwired to a computer. While the shirt is far more comfortable than the other designs presented, the cable routing that the MyoShirt has is not something that the team wants to recreate as it goes completely against the customer requirement of making a fully portable design.

3.2.2.2.2 Existing Design #2: CAREX

The CAREX is a more rigid design than that of the MyoShirt, so the user is not nearly as dependent on the location of the motor mounted system. The CAREX also uses an above head track that allows the user to move wherever they want if there is track available. Again, while this design is effective it is not something that the team wants to proceed with because it goes against the customer requirements of having a portable exoskeleton.

3.2.2.2.3 Existing Design #3: SAM Exoskeleton

While the SAM system is fully portable it protrudes much further than the team would like it to. The SAM has its motors attached at each connection point which causes a very bulky final product. One of the customer requirements set for the team was to not let the system exceed more than ten centimeters off the body and the current SAM system would fail this requirement. Although the team does not like the location of each component, they can be easily moved, and the team does want to improve on this design by implementing a system like this but behind the back of the user making the system much more compact.

3.2.2.3 Subsystem #3: Anchor Points

To have a contraction of a muscle it needs to be anchored along the bone; the anchor point is what connects the tendons from the muscles to the bones. Without an anchor point there will be no contraction, this holds true for the exoskeleton design. To accommodate the existing muscles within the human body, the team plans to add slots along each anchor point to give the user extra room to express their movements. These slots will provide the user with additional freedom to move how they please. The team plans to have two of these types of anchor points for each arm, having a total of four for the entire body. Two points located on a cuff just above the elbow joint, like that of the CAREX system above and the other two points resting along the shoulder joint. Along with the motor attachments along the back, the system will prove to be more than stable and safe enough for the user. Below are a few existing examples of these anchor points being used.

3.2.2.3.1 Existing Design #1: MyoShirt

The MyoShirt does not have any real direct anchor points as the other two designs do because it is a more soft and malleable design rather than a rigid one. With that being said, the MyoShirt does have points at which the bowden cables meet and these points are the back and elbow. While this design is unique and does work, the team does not wish to pursue this because the soft fabric will not allow for a fully potable system. To have a fully lightweight and portable design the team needs to have some rigid components for the batteries and motors to attach to.

3.2.2.3.2 Existing Design #2: CAREX

The CAREX exoskeleton uses a cuff system as its anchor points. There are cuffs located at the shoulder, lower bicep, and wrist. These locations for anchor points are exactly what the team needs for their design. Although the team does not wish to pursue the cuff system as CAREX did, they do want to use the locations for their slot and sleeve design along the lower bicep and shoulder joints.

3.2.2.3.3 Existing Design #3: SAM Exoskeleton

Like the CAREX the SAM system has three anchor points, the difference being on the location. The SAM system has these anchor points located on the biceps, forearm, and the wrist. When it comes to effectiveness and comfort the CAREX system seems to have a better design. Having anchor points along the bicep, especially within a cuff, restricts the movement of the user. Putting the bicep anchor point at a lower region, like the CAREX does which is just above the elbow seems like a better solution.

The requirements for the team are to create an exoskeleton that aids in shoulder mobility, so the only anchor point that needs to be considered are those that are along the shoulder itself and the elbow joint. The SAM systems anchor points and locations are something that the team does not wish to pursue.

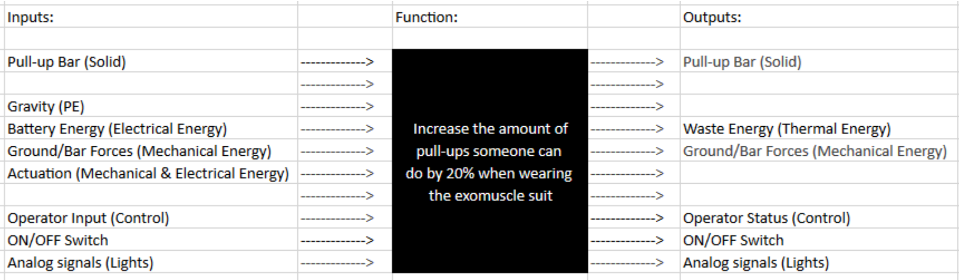
3.3 Functional Decomposition

The purpose of a functional decomposition diagram is to show the hierarchy of the various subsystems within a final product. When breaking down the subsystems of an arm exoskeleton, three main assemblies come to mind, the motor mounting system, cable routing system and the various anchor points that are required to build a stable product. To aid in the decomposition process, the team opted for two different yet effective routes. Firstly, a black box model was constructed which can be seen in the section below. The black box model allowed the team to brainstorm ideas and pull useful information about the design process without revealing or diving too deep into the design phase. The model was able to depict the various forces that will be acting on the system and user, which allowed the team to take these ideas into account when completing their concept generation. After a black box model was constructed and discussed the team wanted to further expand on this idea and go further in depth. To accomplish this a functional flow chart was developed. The flow chart can be seen below and is within section 3.3.2. The flow chart that was constructed went along with the black box model but just went further into detail on what actions needed to be done by the user, and how they are going to be accomplished.

With two different forms of decomposition completed it was time for the team to discuss the three subsystems listed previously and how they should be integrated into an effective exoskeleton. Mounting the motors is a safe and effective location is step one when designing an exoskeleton. The team went through many trials on motor location but eventually decided on a low to mid-back location. Following the motor location, the cable routing was going to prove to an issue. The team decided on routing cables from the back, to over the should and down to the front of bicep. Lastly anchor points. Without a strong and sturdy hold on the cable the motor could not move anything. Putting an anchor point just above the inside of the elbow will mimic the tendons within the arm exceptionally well and will provide a stable connection point for the system. The reasoning behind all the decisions above will be discussed in greater detail in section 3.3.2.

3.3.1 Black Box Model

Below is a snapshot of the black box model the team used when developing their arm exoskeleton. The model was constructed before any designs were discussed and it allowed the team to better visualize a rough outline of the forces and inputs that would be acting on the system and its operator.



Inputs:		Function:		Outputs:
Pull-up Bar (Solid)	------------->	Increase the amount of pull-ups someone can do by 20% when wearing the exomuscle suit	------------->	Pull-up Bar (Solid)
	------------->		------------->	
Gravity (PE)	------------->		------------->	
Battery Energy (Electrical Energy)	------------->		------------->	Waste Energy (Thermal Energy)
Ground/Bar Forces (Mechanical Energy)	------------->		------------->	Ground/Bar Forces (Mechanical Energy)
Actuation (Mechanical & Electrical Energy)	------------->		------------->	
	------------->		------------->	
Operator Input (Control)	------------->		------------->	Operator Status (Control)
ON/OFF Switch	------------->		------------->	ON/OFF Switch
Analog signals (Lights)	------------->		------------->	Analog signals (Lights)

Figure 20: Black Box Model

3.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

Depicted below is snapshot of the flow chart that the team used when developing their arm exoskeleton. The flow chart was constructed after the black box and continued the ideas presented within it. With all the forces discussed from the black box, the team came up with the three main subsystems within an arm exoskeleton and created a flow chart around them to get a better understanding of their operation. On top of this the discussion on each subsystem's role, location and function was brought to our attention. In the section below each subsystem is described in greater detail explaining their purpose, function, and role within the entire system.

(1) Motor Mounting – When thinking about where to attach the motors to the body, many challenges start to arise. Putting the motors on the hip would allow for a much more stable and potentially more comfortable experience, the issue with this is that having motors along the hip will inevitably cause the cables to be much longer which can in turn cause many cable routing issues. The team wanted to avoid as many issues with the cable as possible so putting the motors on the hip was out of the question. It was then thought that maybe the motors should be mounted on the upper trapezius muscle group. This would allow for shorter cables solving the issues depicted above but it is not the ideal location. This is because having the motors so high on the back may interfere with the way a pull-up is performed. Usually, the latissimus dorsi or more commonly known lats, aid the most in a pulling motion that brings the elbows closer to the body. The goal of this project is to mimic the way the human body moves and support that movement with an exoskeleton, and the benchmark test to see any strength increases will be a pull-up which is exactly why the team opted for a mid to low back location for the motors.

(2) Cable Routing - Creating a cable system that is simple yet effective and efficient is going to prove to be the hardest part of this project. Given a motor location of the mid to low back the best route for the cables to travel is from the motor to the top of the shoulder and down the front of the arm and attaching at some point along the bicep. This system will be mirrored along both sides of the body. The routing of these cables will allow for fluid motion of the shoulder joint assisting the user in shoulder mobility. The shoulder being a ball and socket joint allowed for almost 360° of motion. The way that the cables are depicted above will allow for assistance in the frontal raise region of movement but will not accommodate for any movement in the lateral or rear planes. If the team decides to further improve on this design, additional cables in these planes will be implemented.

(3) Anchor Points - Now that the motor location and the cable channels have been discussed, the points at which the cables connect to will be determined. Although the biceps' main purpose is to aid in elbow flexion, the biceps are also responsible for forearm and wrist rotation. The team does not want to implement a fixed anchor point at the bicep because one of these ranges of motion will be compromised. The idea of a slot along the bicep anchor point was brought up and is what the team plans to implement into their design. This will allow for a simplistic design but will not interfere with any actuation or comfort for the user. Again, this system will be mirrored across the body.

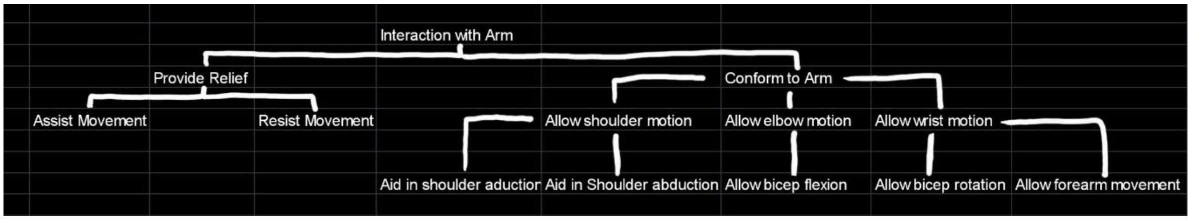
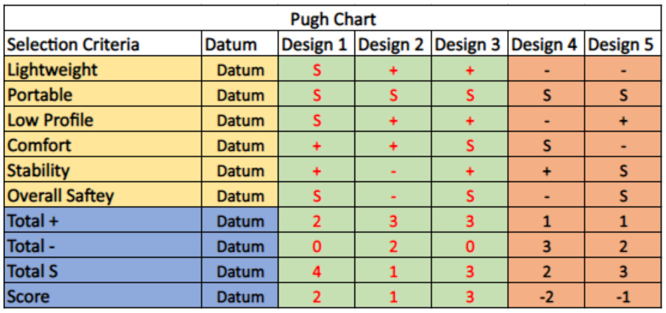


Figure 21: Flow Chart

4 CONCEPT GENERATION

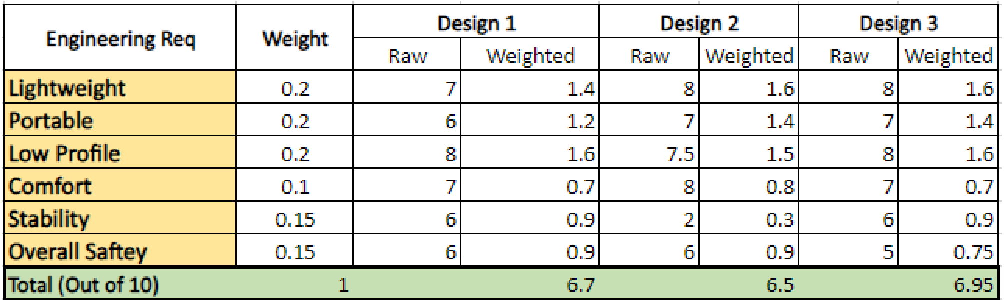
The team's concept generation was a process that went on for about a week. We came together with many designs and together through discussion chose the first designs to put into a Pugh Chart which is seen in Figure 7. The Pugh chart was only given design that the team though best represented the scope of the project as some did not meet certain requirements.



Pugh Chart						
Selection Criteria	Datum	Design 1	Design 2	Design 3	Design 4	Design 5
Lightweight	Datum	S	+	+	-	-
Portable	Datum	S	S	S	S	S
Low Profile	Datum	S	+	+	-	+
Comfort	Datum	+	+	S	S	-
Stability	Datum	+	-	+	+	S
Overall Saftey	Datum	S	-	S	-	S
Total +	Datum	2	3	3	1	1
Total -	Datum	0	2	0	3	2
Total S	Datum	4	1	3	2	3
Score	Datum	2	1	3	-2	-1

Figure 22: Pugh Chart

From the Pugh Chart we discovered that designs 1, 2 and 3 were the best as seen from their total score. These designs were then put into a design matrix which looked at each individual design on a more focused level. Seen below in Figure is the design matrix that the team created to evaluate the remaining designs and choose a final one.



Engineering Req	Weight	Design 1		Design 2		Design 3	
		Raw	Weighted	Raw	Weighted	Raw	Weighted
Lightweight	0.2	7	1.4	8	1.6	8	1.6
Portable	0.2	6	1.2	7	1.4	7	1.4
Low Profile	0.2	8	1.6	7.5	1.5	8	1.6
Comfort	0.1	7	0.7	8	0.8	7	0.7
Stability	0.15	6	0.9	2	0.3	6	0.9
Overall Saftey	0.15	6	0.9	6	0.9	5	0.75
Total (Out of 10)	1		6.7		6.5		6.95

Figure 23: Design Matrix

The design that was chosen from the design matrix is seen below and was design 3. After discussion with the client and a redirection in the way we were thinking lead to a new design that the team came up with that would be the new final design instead of the one chosen from the design matrix. This design is called the final design and includes a chest harness for mounting motors, using the existing chain drive system that the lab has provided, and uses an anchor point on the upper arm to assist with the planar motion that the client requested. The team was originally designing a device to specifically help with the muscles found in pullups which lead to the team designing a full arm model. The client wanted to redirect us to focus more on the shoulder and movement in the plane perpendicular to the body.

4.1 Full System Concepts

Below is a review of the designs chosen from the Design Matrix and the final design that we made after we spoke with the client.

4.1.1 Full System Design #1: Shoulder Specific Design with Chain Drive

The design shown in Figure is the design that we came up with after talking to the client about the design that was chosen from the decision matrix and redirected onto a different path. This design will be able to interface with the other suits that the client is currently working on and use the same drive system. Pictured in red is where the motors will mount. The motor uses a chain that mounts onto a Bowden cable which is seen in blue. The chain allows the motor to apply 2 directions of force which allows the design to apply force in two directions. This will allow the Bowden cable to assist and lift as well as lowering the arm of the person wearing the suit. A negative to this design is the mounting situation. We will have to mount two different motor-chain interfaces on the back which will make it hard to stay under the weight requirement given for this project, however, the client has stated that the weight can be surpassed if needed for prototyping purposes.

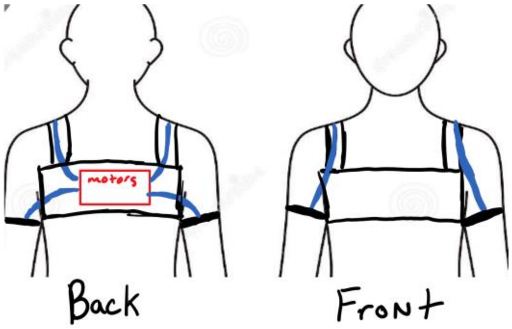


Figure 24: Final Design

4.1.2 Full System Design #2: Single Arm Winch

This design is seen in the design matrix as ‘Design 1’. This was created when the team was tasked with making a design for the whole arm which was before the client meeting which gave us redirection. Pictured in black is the vest which the motors and the pully assembly mounts to. This design has BOA hubs for the ability to resize which is a big pro for this design. A con is the fact that this would be much more difficult to convert into a two-arm design with geometry.

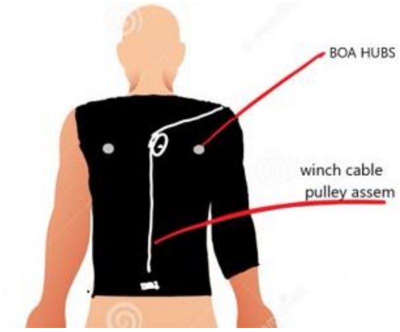


Figure 25: Original Design 1

4.1.3 Full System Design #3: Dual Shoulder-Mounted Motors

This next design is seen as ‘Design 2’ in the design matrix which was the lowest scoring design from the original concept generation. This design has two motors mounted at each shoulder which would be able to coil each arm separately. This design was made for full arm assistance not just assistance for the shoulder. This means that this design would interfere with what we are trying to interface with. Pros to this design are the fact that the mounting on the back is very simple and can give different degrees of assistance to either arm. The cons to this design are the weight increase from having two motors mounted to the back of the user and being able to operate the motors separately based on the needs of the user.

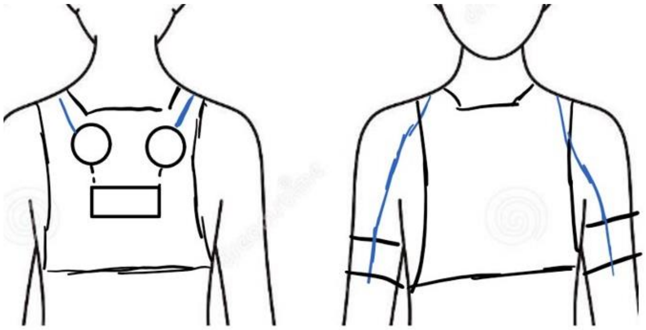


Figure 26: Original Design 2

4.1.4 Full System Design #4: Single Coiling Motor on the Back

This design is seen as ‘Design 3’ in the design matrix and came out with the highest awarded score among the 3 designs in the design matrix. This design has a single motor mounted on the back with two cables (seen in blue) coiling in opposite directions to pull the arms. The pros to this design were that a single motor greatly reduces the weight of the design, one motor coiling both arms allow us to reduce the complexity of the design as we do not need to code the two motors to move simultaneously. Cons to this design are that one motor may not have the strength required to help the user, and there is no variation in the assistance for different arms.

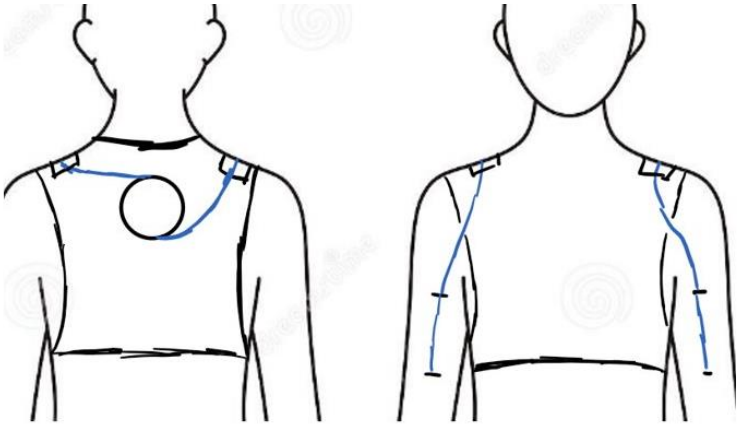


Figure 27: Original Design 3

This is the design brought to the client with the intention of this being the final design. As previously stated, the client wanted to offer more direction as they felt we were misled with what was wanted. The result of this meeting is seen in *Figure 17* with the new final design.

4.2 Subsystem Concepts

To create the final design, the team broke the problem into 3 subsystems: The motor mounting, the arm mounting, and the cable routing. These are the 3 main components that must go into the design for it to work properly.

4.2.1 Subsystem #1: Arm Mounting

One of the main subsystems is arm mounting. This determines how the Bowden cables will mount onto the arm. There were two designs that the team was going back and forth on.

4.2.1.1 Design #1: Tube Arm Mount with horizontal Track

This first design is like a flexible, rigid tube that will be placed onto the arm which will give the Bowden cables a surface to mount to. As seen in the below figure the tube will have a rail which will keep the force acting in the correct plane as to move the arm vertically in the plane perpendicular to the body.

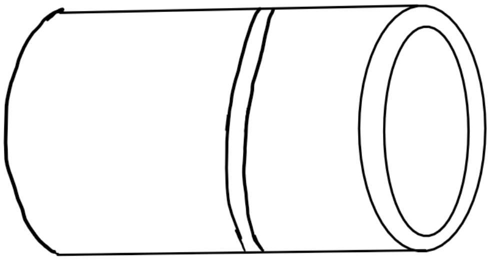


Figure 28: Arm Mounting Design 1

This design has the advantage of being rigid enough as to where great force can be exerted and this arm mounting design will be able to withstand the force being exerted. The groove in the center is used for mounting the Bowden cable with a track what will allow the cable to self-correct when the user turns their arm. This means no matter what orientation the user's arm is in the force will be applied vertically. A con to this design is the bulkiness and lack of adjustability between users. This specific design will not be able to be adjusted for someone with a larger or smaller arm meaning that a new arm mount will have to be made for different users.

4.2.1.2 Design #2: Adjustable Arm Mount

Design 2 used a similar design for mounting the Bowden cables with a mounting strap seen in blue. The Bowden cable will attach to this and be able to self-orient like design 1. Where this design differs is the actual mounting system on the arm. This design is like a strap that can be adjusted around the arm using Velcro like a blood pressure arm cuff where the strap can be changed based on the size of the user's arm. The pros to this system are the self-orienting Bowden cable attachment, and the adjustability for users with different arm sizes. However, this leads to the cons as the arm mount is not made from a rigid material. This gives it adjustability but takes away some of the stability and subsequently this design will not be able to withstand the same forces as design 1.

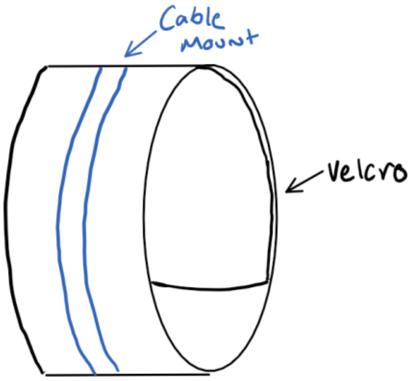


Figure 29: Velcro-Based Arm Mount with Self-Orienting Cable Attachment

4.2.2 Subsystem #2: Cable Routing

Cable routing is another subsystem that we have made a subsystem. This is one of the most important aspects of the design as it determines how force is transferred from the motor to the arm.

4.2.2.1 Design #1: Over Shoulder Cable Routing

The main design that we made is having 2 Bowden cables per arm. One cable for movement up and another for downward movement. Having the cable anchored at the top of the shoulder will give the arm the moment required to help lift the arm up. The trouble with this is making sure that the top of the arm is receiving enough force to adequately assist with upward movement. That would be a con to this design. It will be more difficult on the motor to lift the arm from this configuration. A pro to this is the simplicity in mounting the Bowden cables as they are directly connected to the mount on the arm.

4.2.2.2 Design #2: Force Transfer Over Shoulder

A second design for the cable routing includes a transfer system to help transfer some of the force to adequately lift the arm. This will act as a lever to help transfer the pull from the motor to the mount on the arm. A con of this design is that this will protrude more than allowed in the requirements if done incorrectly. This will also make everyday movement more cumbersome as this will get caught on hair, clothes, and any similar objects. The green in the figure below is the cable coming from the motor, while the red is that cable mounting to the arm.

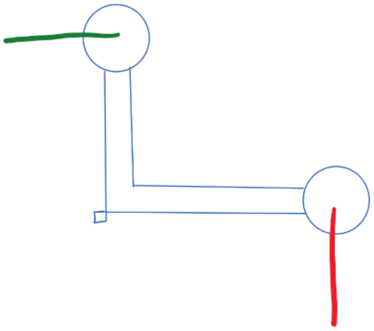


Figure 30: Lever for Transferring Force to Arm

4.2.2.3 Design #3: Under Arm Cable Mounting

The last design for this subsystem is the under-arm cable mounting. The specification of the revised design needs assistance while lifting and lowering the arm. This is where the under-arm mounting comes in. The motor is interfaced with the chain and Bowden cables for a force in two directions, this second direction will be mounted under the arm and onto the same arm mount which will be able to pull the arm down along with keeping the cable properly oriented.

4.2.3 Subsystem #3: Motor Mounting

The last subsystem that we defined was the motor mounting which completes the three main components of the design. It has already been discussed that we will be using a motor-cable interface that the client has already made to simplify the number of parts needed in their total project. This is just discussing how we would mount the motor assembly on the back.

4.2.3.1 Design #1: Belt Attachment for the Motors

The first design that was talked about is using a belt made of leather around the chest which will give the motor an appropriate place to mount and a rigid base to exert force from. The pros to this include being very light weight as all that will be needed is the belt to mount, another pro is a belt offers a stable base for mounting and operating the motors. The cons of this would be restricting the breathing of the user, the belt is not a flexible material meaning if tightened the user may not be able to expand their chest to breath or it will be significantly harder. A second con is the possibility of the belt to slide down the body while in use. Without shoulder straps the belt may fall which could possibly hurt the user or break the motors.

4.2.3.2 Design #2: Posture Corrector for Motor Mount

The other design that we had for motor mounts would be using something like a posture corrector. Pros to this design are having a common geometry for the shoulders and back. A posture corrector will correct the geometry of the back and shoulders of people of all sizes meaning we can design to the consistent geometry the design will have more consistency with people of different sizes. The posture corrector will also provide a stable place for the motors to mount and pull from. The cons are that we would have to design a posture corrector that can be sized to multiple people with different body types or buy one online which we would then have to design a motor mount to work specifically with that design. Both cons can be worked around and will have to be discussed further with the client.

5 DESIGNS SELECTED – First Semester

After going through a Pugh chart, decision matrix and two different sets of concept generation, the team was ready to finalize their design. Below in chapter 5 the reasoning behind the choice of the final design will be discussed as well as the technical selection criteria the team followed when doing this.

5.1 Technical Selection Criteria

When determining what technical criteria the team should follow, the team went back to look at the customer and engineering requirements and then made the technical requirements based off these. The technical requirements that the team decided on are as follows:

- Lightweight
- Portable
- Low Profile
- Comfort
- Stability
- Safety

With all the technical requirements set, the team implemented them into both a Pugh chart and decision matrix. Along with these requirements the team had set a datum so they could compare each design in a fair and non-biased manner. Once this was complete the team had a design that they felt comfortable with and could see working exceptionally well. In the following section the final design will be discussed in greater detail.

5.2 Rationale for Design Selection

The top two designs shown share many features that overlap, however some customer requirements changed within the most recent meeting with Dr. Lerner and more requirements were introduced. Design one had been designed in accordance with the initial customer requirements. The device was now an assistance device in an industrial environment rather than a therapy motivated device. The device had to then apply assistance in both the pull up and the press motions to conform to the new customer requirements.

The first of these designs featured a motor actuating both arms under the assumption that the main accomplishment of the device was to increase pull up assistance for the user. Thus, the joint that was most beneficial to assist was the elbow, allowing for the most assistance over the longest range of motion during the action of the pull up. The design was highly rated in regards of weight because it accomplishes actuation of both arms while only utilizing one motor.

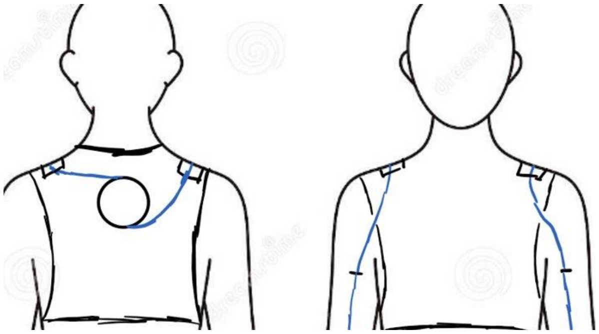


Figure 31: Design 3 (Preliminary Customer Requirements)

The customer requirements were then changed meaning a complete redesign occurred in order to meet the desired goals of the device. Due to the necessity of assistance in both directions and the lack of elbow assistance the design would be reconfigured using new actuation technology provided by Dr. Lerner the final design was drawn up this allowed for actuation in both the pull up direction and press direction this used to motors but is ultimately beneficial due to the power output of the motor itself. The design is shown below in Figure 16.

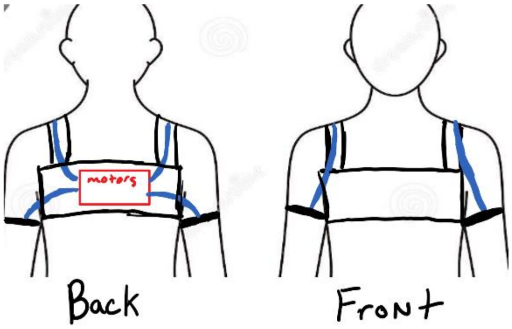


Figure 16: Final Design

The new customer requirements included the ability for the device to hold the user's arm in a horizontal position under little to no force exerted by the user the user. The primary reason behind this requirement being that in an industrial environment the user be working on or holding something above their head, for long periods of time. The device should have the ability to reduce or eliminate the weight of the user arm plus any added weight of tools or object held in this position. With this knowledge calculations can be performed on both systems to understand whether they are viable with for this constraint. For this data the average weight of a human arm was measured to be about 2.5 kg. Since the device is intended for industrial use the weight of an average hand tool was factored into this as well bringing the total weight to 2.72 kg. Calculation of the sum of the moment around the shoulder with one's arm extended horizontally reveals that the required torque to offset this would be around 8.5 Nm. Design 3 shown in Figure 17 above not only actuates both arms simultaneously but only use one motor to do so. The motors provide about 3 Nm of torque at normal operation levels with the motor maxing out around 9 Nm. If the standard sized motor were to be used under its maximum operating levels it would still not provide enough torque to offset the weight of both of one's arms.

The final design located in Figure 16 allows for a much better weight per motor ratio while also allowing for independent actuation of arms. The toque output through this design would be close to 9 Nm about the shoulder at normal operation torque giving plenty of power to allow for a fully extended horizontal arm with no muscular input from the user. Under peak power this jumps to around 27 Nm or torque allows for a significant weight held weight to be offset by the device. This increase in assistance power comes at the cost of weight, however for the gain received from this design change it far makes up for its added weight. The other added feature based due to the geometry of cable routing in the final design is that the further the arm is raised the greater the force exerted with every position after horizontal arm placement experiencing less mechanical advantage exerted by the arm. As discussed, prior the final design also has the advantage of assisting in the downward direction as well, since the same motor will be used to actuate this Bowden cable and the geometry is remaining relatively similar the same assisting torques can be expected in the opposite direction as well, with the system becoming more efficient the closer the arm gets to its lowest position. The motor mount in this design will also experience a tension force in the direct direction of the cable output. Though there are two Bowden cable outputs for each motor mount only one will be experiencing a tensional force at any given time. This has a direct dependence on which direction the user's arm is currently loaded in. Since the cables are a rigid system with little stretch to factor in the force in which the motor mount could experience is essentially unlimited. This would be a case which would only happen once an object of mass overpowers the human arm, essentially forcing it in a motion in which the muscular system could not account for. As this is not a planned force and the device design in question is not a rigid exoskeleton, and is closely defined as an exomuscle, it still relies on the structure of the human body to remain functional. Thus, what can be assumed about expected forces on the motor mount itself would be only applied by the force of cable retraction from the motor. With an expected force at normal operation output of around 120 N and at peak power a force of around 360 N. With the current harness subsystem which is responsible for attachment of the motor mounts to the user these applied forces will be within the range of what the current designated strapping material can handle.

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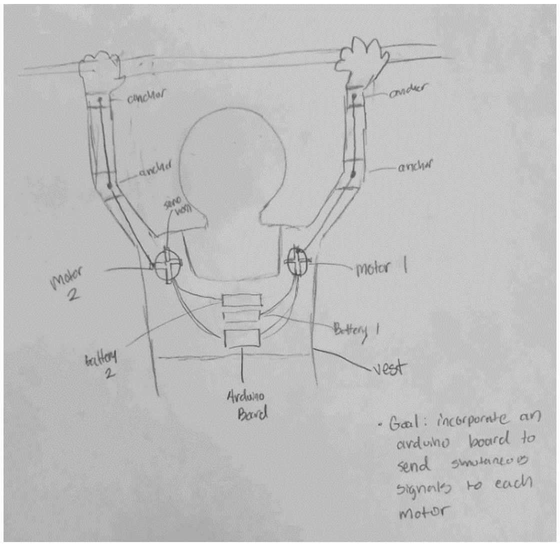
7 APPENDICES

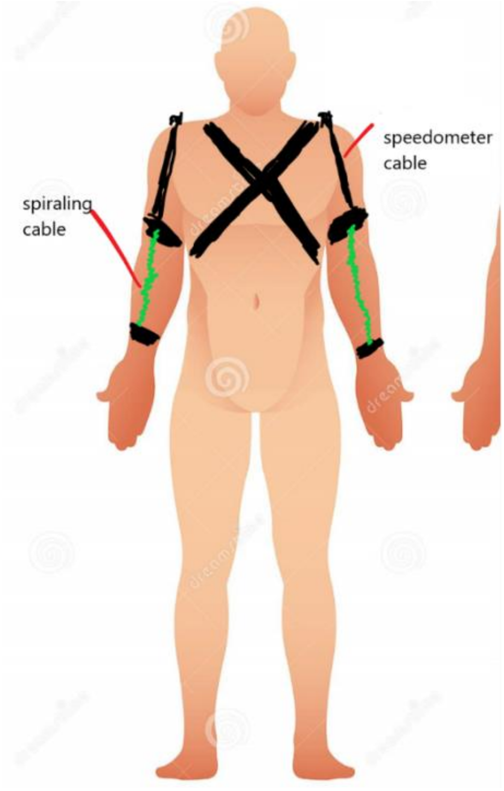
7.1 Appendix A: Design Concepts

Design 1 –

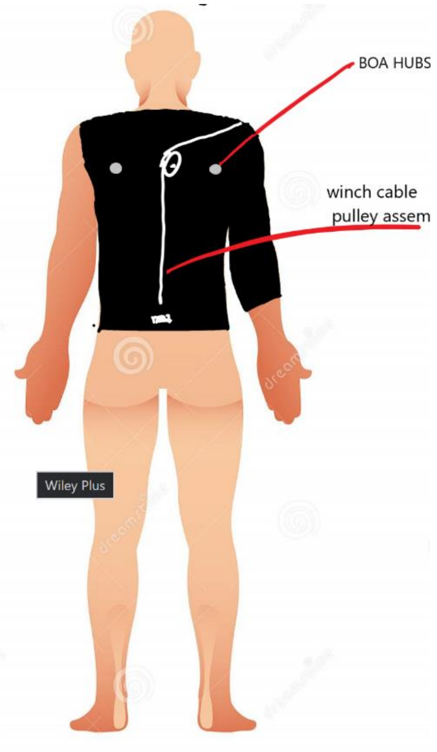


• Goal: incorporate an arduino board to send simultaneous signals to each motor

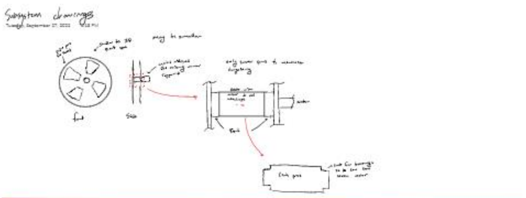
Design 2 –

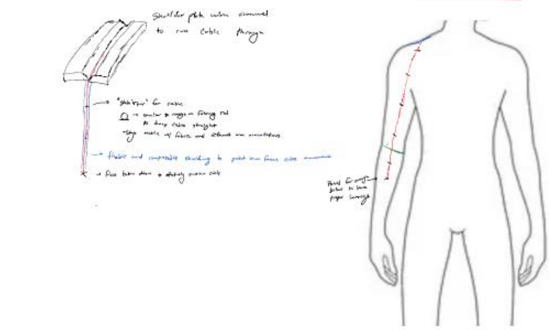


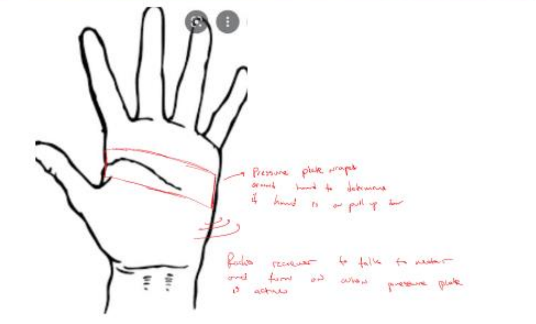
Design 3 –


BOA HUBS
winch cable
pulley assem
Wiley Plus

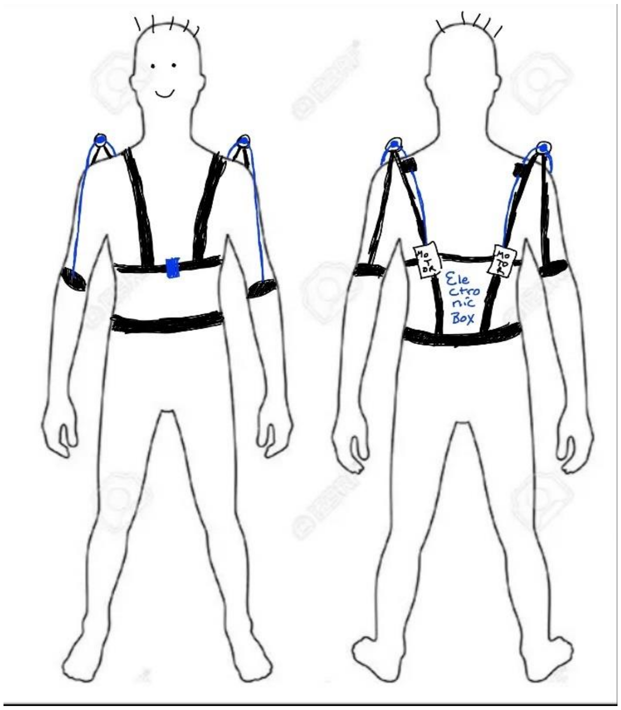
Design 4 –


Subsystem drawings
front
Side
Cable guide

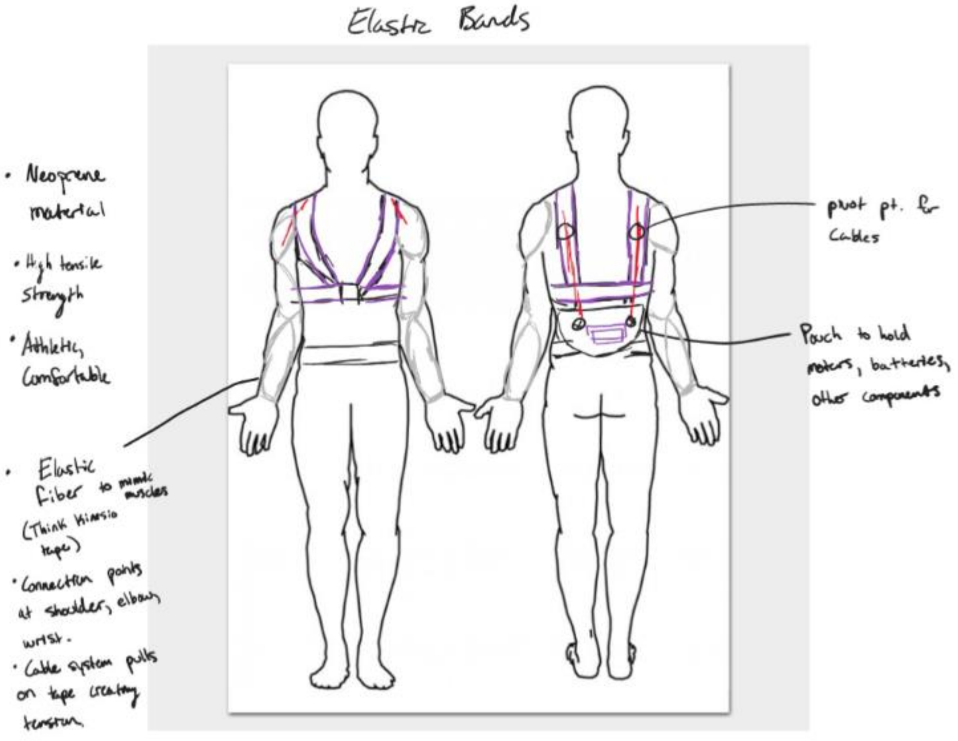

Shoulder plate with channel
to run cable through
"stair" for cable
Ω → similar to ... fishing rod
to keep cable straight
flexible and compressible shielding to protect ... cable
→ ... to ... cable


Pressure plate wraps
around hand to determine
if hand is on pull up bar
Radio receiver to talk to winch
and turn on when pressure plate
is active

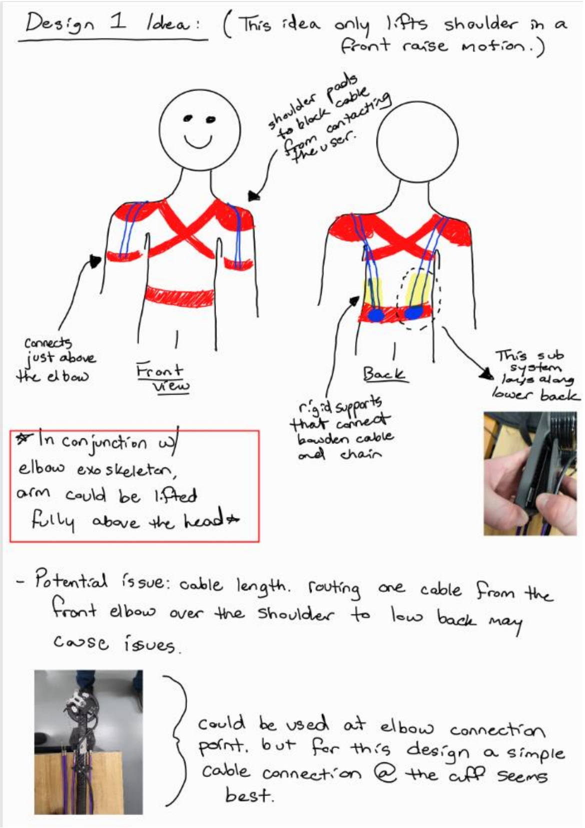
Design 5 –



Design 6 –



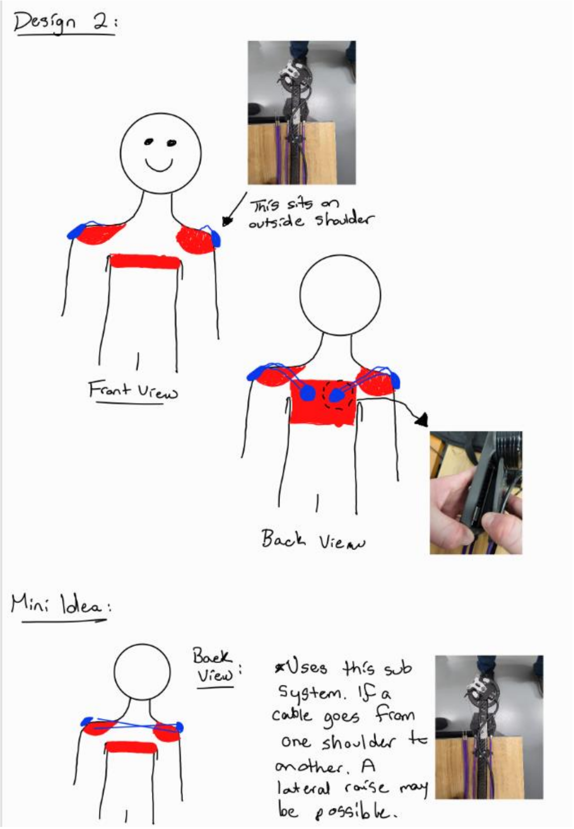
Design 7 –


Design 1 Idea: (This idea only lifts shoulder in a front raise motion.)

☆In conjunction w/ elbow exoskeleton, arm could be lifted fully above the head☆

- Potential issue: cable length. routing one cable from the front elbow over the shoulder to low back may cause issues.

could be used at elbow connection point. but for this design a simple cable connection @ the cuff seems best.


Design 2:

Mini Idea:

☆Uses this sub system. If a cable goes from one shoulder to another. A lateral raise may be possible.

7.2 Appendix B: SOLIDWORKS FILES

3D Model of the Motor –

Model of Motor Mount –