Robotics and Automation – Arm Exoskeleton

Engineering Model Summary Deliverable

ME486C

P11: Arm Exoskeleton

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DISCLAIMER

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Top Level Design Summary (10pts)

CAD Models and Subsystems

The Robotics team has been tasked by Dr. Lerner to improve upon and design a unique arm exoskeleton that can assist its user with pullups, and a variety of daily activities. The design will focus on the upper arm providing support and stability for the user during activities. There is not yet a final design for this project, but the team currently has three different unique and effective prototypes. This will be narrowed down to one design in the coming weeks once the team meets with Dr. Lerner and a final design is finalized. The CAD models for all three designs can be seen below.

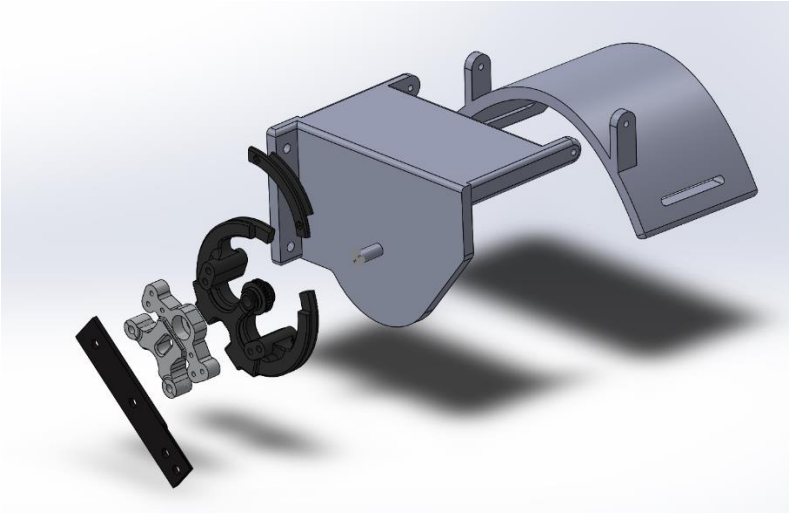


Figure 1: CAD Model Prototype 1

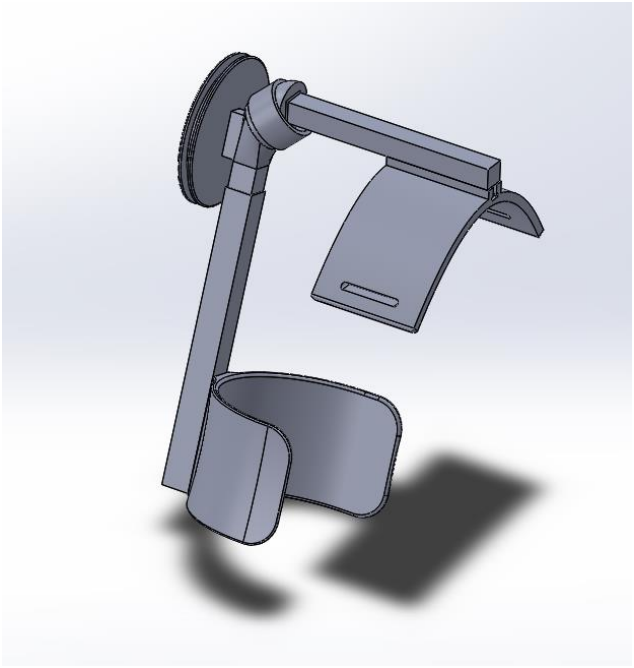


Figure 2: CAD Model Prototype 2

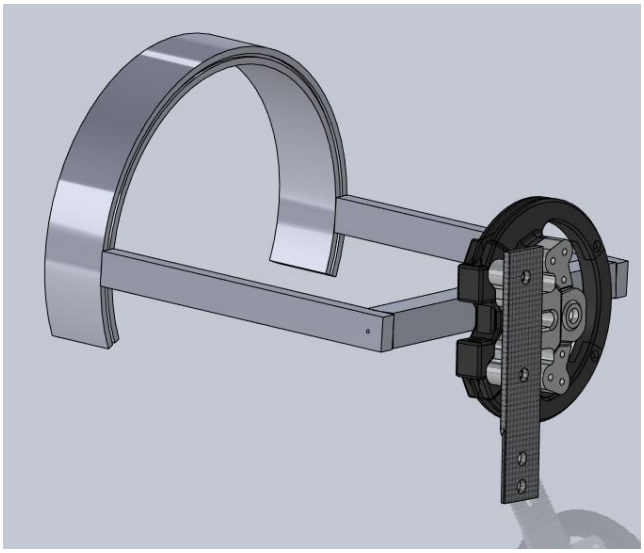


Figure 3: CAD Model Prototype 3

Prototype 1 Sub-systems and Function

This is the first design that the team came up with. It features a shoulder hinge plate to allow for movement in the lateral direction as well as a Bowden cable/pulley system to aid the shoulder with movement in the frontal direction. The team was able to test this design last semester with a PLA build. After testing the team discovered that the arm could not go past or even reach parallel in the lateral direction. The hinge plate would bind on the shoulder plate and itself, in addition to this the shoulder plate would also not stay flat. The team is confident that what caused the shoulder plate to keep lifting off the user was the lack of restraints and an effective harness system. To combat this critical error, the team will add additional harness' across the body and are also looking into a posture corrector as the main form of restraint and attachment for the system.

Prototype 2 Sub-systems and Function

Following the issues with the first prototype the team decided to redesign the shoulder joint for a more optimal variation, and one of those redesigns implemented a ball and socket joint. This redesign of the joint mimics the actual shoulder joint of a real person. The ball and socket design will allow for the degrees of freedom that a real shoulder would have. The ball joint will have to be made out of a ceramic material such as a pool ball or something similar in strength. A pool ball will be beneficial to the team during the testing process. This is because all of the forces applied to the system are going to travel to this joint and the tensile strength of the material must be high enough to withstand the forces. Although ceramics are very brittle, as long as the chosen ceramic is tough enough the team will not need to worry about a potential shatter. Additionally, the ball joint will not be powered it is there to provide stability and movement, the only direction that will be powered is the frontal plane. A simplified version of the pulley system from the first prototype will be integrated into the ball and socket prototype. This pulley system will feature a single cable wrapped around a wheel, while like the original pulley, this version will be far simpler and much easier to manufacture.

Prototype 3 Sub-systems and Function

As stated above following the issues of the first prototype the team redesigned the shoulder joint. Prototype three implements a winch system to the shoulder allowing for the lateral movement, and a similar mechanism for the frontal plane movement.

One of the main problems with the first prototype is its inability to help when the arm is extended parallel to the body. This design was created to help solve the mobility issues. At first the design featured a bar that would extend across the users back and chest to provide support. However, this limited the movement of the shoulder entirely. To enable this movement the shoulder supports have been placed on a rotating track that will allow the entire support system to move back and forth allowing the bars to turn reducing stress on the user's shoulder.

Customer and Engineering Requirements

Given the new world of exoskeletons and especially upper body ones, there needed to be a few parameters that the team would need to follow. Dr. Lerner gave the team a set of guidelines that shaped the teams designs but did not limit their creativity and design process. The customer requirements that the design must include are:

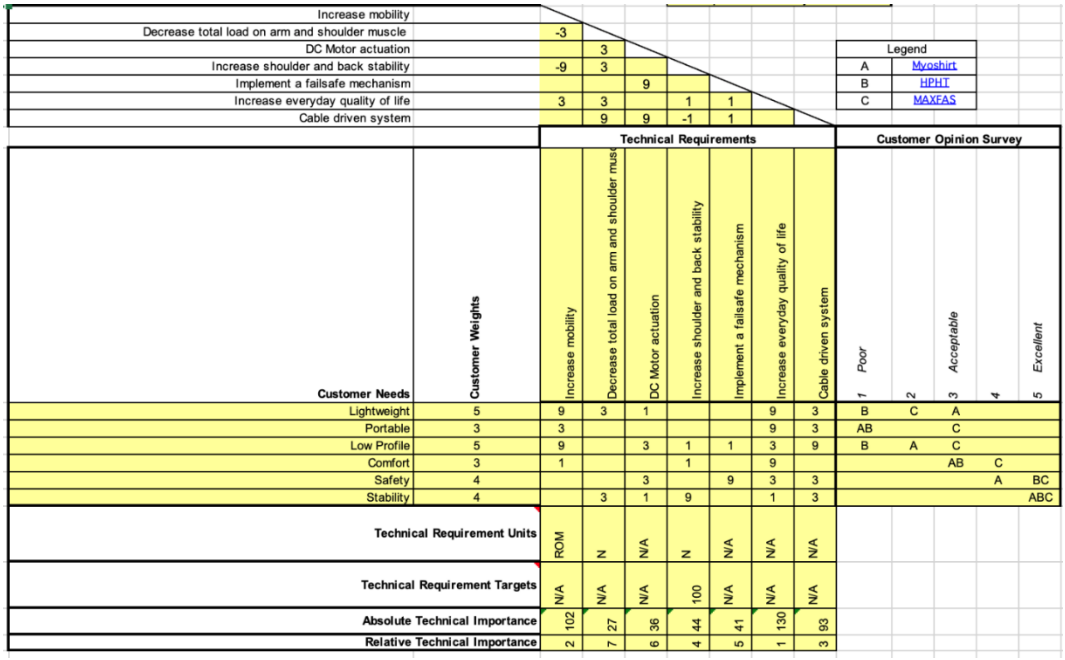
1. Safety
2. Comfort
3. Portable
4. Stable
5. Low profile
6. Lightweight

With these customer requirements set, the team was able to create a set of engineering requirements, those requirements can be seen below.

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.

House of Quality (HoQ)

With all the customer and engineering requirements set, the team decided that creating a HoQ (House of Quality) would best aid the team in comparing their requirements. The HoQ was able to give the team additional guidance when creating their three prototypes. Below is a snapshot of the HoQ.



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										
		Technical Requirements														
Customer Needs	Customer Weights	Increase mobility	Decrease total load on arm and shoulder mus	DC Motor actuation	Increase shoulder and back stability	Implement a failsafe mechanism	Increase everyday quality of life	Cable driven system								
Lightweight	5	9	3	1			9	3								
Portable	3	3					9	3								
Low Profile	5	9		3	1	1	3	9								
Comfort	3	1			1		9									
Safety	4			3		9	3	3								
Stability	4		3	1	9		1	3								
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								

Legend	
A	Myoshirt
B	HPHT
C	MAXFAS

Customer Opinion Survey										
	1		2		3		4		5	
	Poor				Acceptable				Excellent	
Lightweight	B		C		A					
Portable	AB				C					
Low Profile	B		A		C					
Comfort					AB		C			
Safety							A		BC	
Stability									ABC	

Figure 4: House of Quality

Summary of Standards, Codes, and Regulations (20pts)

The team will be continuing the design of the robotic arm exoskeleton with the listed standards and codes found in Table 1. The Engineering Code of Ethics is a useful set of standards regarding engineering practice. For this project, it is the team's responsibility to engineer a device that has zero potential to harm an individual or their property while it is being tested on an individual. Human testing follows a strict set of requirements for it to be an ethical process so the team will be abiding by these requirements when the testing procedure begins.

The ANSI and ISO standards for wearable medical devices will guide the team ethically design a device to be worn by an individual. These standards outline what Good Clinical Practice looks like when testing on individuals. The ISO standard 14971 specifically identifies risks in the device throughout its life, so these standards provide maintenance procedures and what those should look like for wearable medical devices.

Table 1: Standards of Practice as Applied to This Project

Standard Number or Code	**Title of Standard**	**How it applies to Project**
ASNI/AAMI HE 74:2001	Human Factors Design Process for Medical Devices	Helps in the design of how the device with interface with the user in a safe manner.
Engineering Code of Ethics Section II-1-a	Engineers shall hold paramount the safety, health, and welfare of the public.	"Engineers' judgement is overruled under circumstances that endanger life or property; they shall notify their client as may be appropriate." Helps authenticate safety of device operating from user.

ANSI ISO 14971	Application of risk management to medical devices	Helps identify and control risks through device life for wearable medical devices.
ANSI ISO 14155	Clinical investigation of medical devices for human subjects -Good clinical practice (GCP)	Provides guidance to manufacturers on how to implement GCP for clinical investigations. Protection of patient rights, ethical considerations for trials on humans, etc.

Summary of Equations and Solutions (35pts total)

A shoulder exoskeleton is a very complex system that uses a wide variety of unique attachments and components. With so many moving pieces there is a room for multiple potential failures at these "load points." In an exoskeleton, the potential failures are mainly concerned with degrees of mobility, force concentration on a specific point, and the exoskeleton actuation method. Potential failures are listed below that pertain to each of these categories and they will summarize how they jeopardize the design.

(1) Mobility freedom due to user connection: The initial prototype featured a hinge connected to a plate that rested on the shoulder. This allowed for the user to raise their arms laterally while the pulley allows for frontal raises. The problem with this is that the hinge was too wide making the device unusable once the arm was frontally raised to about 45 degrees. This information is taken from the Scapulohumeral research analysis that identified weak points in the prototype along the shoulder plate and joint.

(2) Deflection of lever arm: The lever arm is quite an important component for the design since it's the bridge between the pulley to the square stock bar that connects the cuff to the user. A design analysis showed that the current state of the lever arm is too thin for the loads that the design could endure. The analysis showed that the lever arm will deflect beyond the team's safety factor and should redesigned. This analysis utilized moment of inertia and cantilever deflection formulas to calculate the optimal shape, and amount of deflection in the bar that is suitable for the prototype design.

(3) Bowden Failure due to Tension: In all three prototype designs, Bowden cables are used to rotate the motor and operate the system. This load case utilizes property characteristics to compare with motor characteristics to determine if failure is possible.

The team's analysis from the previous semester addressed the potential failures for the current prototype at that time. The solutions presented here will describe how each of the above-mentioned load cases were resolved.

Load case one, the most important to the design, is the mobility range of the user. It's most important since that's what an exoskeleton needs. The exoskeleton design replicates the user's motion while aiding that the user can no longer achieve on their own. The arm exoskeleton in this project was previously limited to how much the user's arm could move frontally and laterally. The team identified this as the shoulder plate and hinge connection that needed to be redesigned. The current prototypes feature sliding shoulder plates along with a ball joint replacing the hinge. The ball joint adds at least 90 degrees of freedom laterally, and the team is hoping to test for greater than 90 degrees in the frontal direction. Scapulohumeral rhythm best defines what the ball joint and sliding plate will accomplish.

Although untested, the team is aware that to achieve this natural rhythm the components of the shoulder will need to operate in tandem. An analysis of the updated prototype will prove that the ball joint system offers the flexibility necessary to achieve full range of mobility.

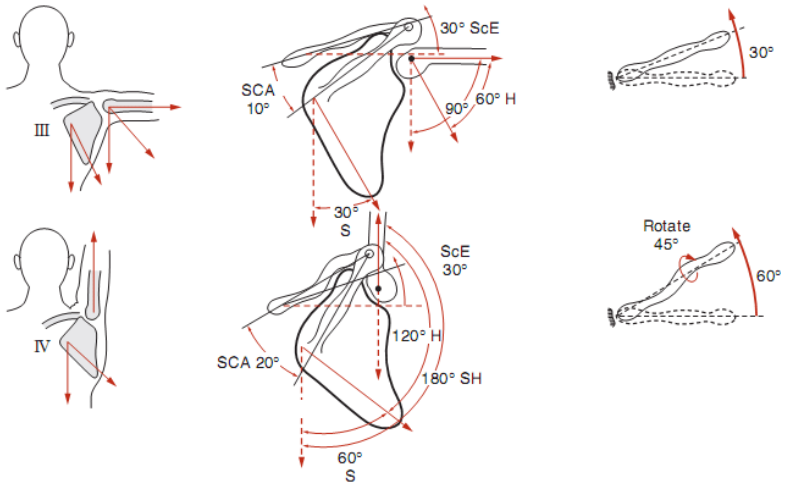


Figure 5: Scapulohumeral Rhythm

Load case two describes the deflection of the lever arm. There are other parts of the design that endure forces but none yet that have needed testing. The lever arm and pulley are the main components that endure any kind of loading that could cause failure in the design. One analysis shows that the previous curved shape of the bar is not enough to withstand the forces the design will endure. The shape has since been changed to a rectangle, as shown in figures X and X. The second analysis conducted showed that the bar is too thin and still deflects more than the team can allow. There are multiple ways the team can correct this failure. The final design will use Onyx or Carbon Fiber filament to be inlaid with the bar so that its strength is greater. Another way to fix the deflection is to increase the thickness of the bar. The current bar orientation allows for deflection across a small area, so increasing that area will provide enough resistance to where the deflection is almost negligible. The following is an excerpt from the analysis that calculated the numerical result: "…changing the beam thickness to 12mm from 2.67mm (.47in from .1in), the moment of inertia becomes 2736mm4. If all other factors remain the same the deflection of the beam becomes .164mm downwards which is roughly .006in."

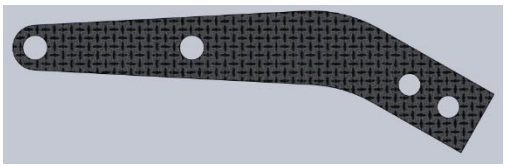


Figure 6: Lever Arm Adapter (Before)

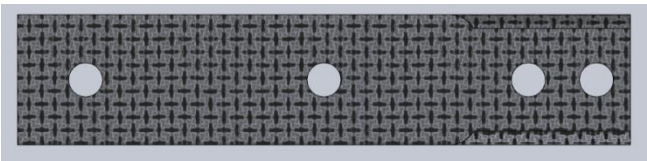


Figure 7: Lever Arm Adapter (After)

Load case three is that the cables will fail due to tension. Not backed by calculations but backed by the code of ethics is that any design to be used or worn by an individual must be safe. Safety is an important part of the design, thus the concern of cables snapping on this cable operated device. The initial prototype used wire cables which have a very high strength against snapping, but the possibility is still there. The team plans to incorporate Bowden cables to correct this potential failure. Bowden cables are encased in their own sheath which will protect the user from any stray wires. The team will also ensure the wires are not loosely hanging on the user and will be routed throughout the body of the design.

Table 2: Component Minimum FoS

Sub-system	Part	Load Case Scenario	Material	Minimum FOS
Attachment Harness				**1.4**
	Harness	Tension force of 340 N applied to Harness at motor mount location.	Polyester Webbing	1.4
Shoulder Mount/Hinge				**1.5**
	Shoulder Plate	Compressive Force of 25 N located above the shoulder due to harness tension.	Black TPU Filament	4.3
	Hinge Plate	Torque of 5 Nm applied at the hinge arms due to user's natural arm rotation in arm raise.	Onyx 3D Printer Filament	1.5
Shoulder Actuation				**1.1**
	Large Pulley	Shear force of 120 N applied to un-webbed regions of pulley.	Inlayed Carbon Fiber Onyx Filament	1.6
	Large Pulley Bridge	Shear force of 120 N applied to pulley bridge.	Inlayed Carbon Fiber Onyx Filament	1.6
	Shoulder Lever	Shear force of 50 N applied at mount joint of the shoulder lever and tube.	Carbon Fiber Flat Stock	1.2
	Shoulder Tube	18 N force applied on attachment point to lever arm.	Carbon Fiber Square Stock	1.5
	Bicep Cuff	18 N force applied laterally upon actuation of device.	Black PLA Filament	1.1
	Flat Anchor	8.3 Nm torque applied at screw holes.	Onyx 3D Printer Filament	1.6
	Bowden Cable	Tensional force of 120 N applied via motor.	Steel Cable	2.3

The team has determined that the hinge assembly is the largest factor which plays into the desired Scapulohumeral rhythm. The ball joint will effectively take the place of the hinge plate providing a better replication of the shoulder's movement. This changed the structure and fu8ndementals of how the pulley operates as well. The Ball joint now acts as the hinge plate and the fixed pulley mount. The Shoulder lever will most likely be eliminated from the design. This is the most logical option as the shoulder tube is more than capable of accomplishing both the task of mounting and positioning the cuff as well as acting as the shoulder lever. This will eliminate unnecessary complexity as well as providing a far more rigid structure to the post pulley mounting system. Finally, the Bowden cables will be a close substitute to the cables that were previously in place this change will not alter the design much however there will need to be an addition of sheath retainers ultimately prevent the sheath of the Bowden cable from moving with the cable itself. This will effectively allow the inner core of the Bowden cable to move independently of its sheath.

Functional Flow Chart for Testing Procedures

The flow chart below outlines the testing procedure we will present to Dr. Lerner for feedback. Previously our client mentioned he wanted the design to be able to perform an assisted pull up, however we want to broaden our testing procedures to measure endurance, strength, and mobility to evaluate the performance of the device. The tests will be repeated by all members of the team to record multiple sets of data and will be compared to a baseline of the exercises without the device. This flowchart will be presented in the upcoming meeting with Dr. Lerner to get his opinion and add any changes he will want.

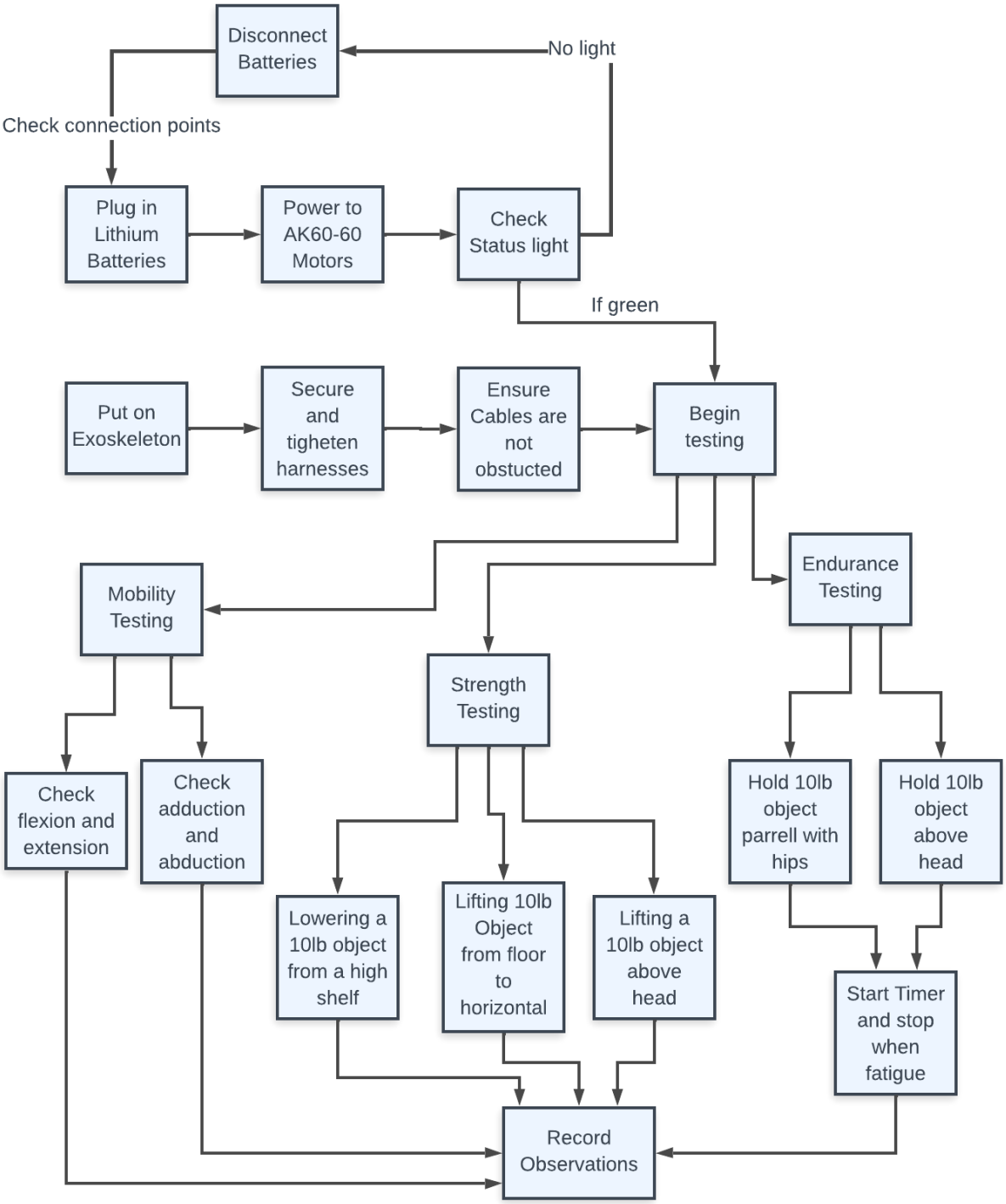


Figure 8: Testing Procedure Flow Chart

Moving Forward (15pts)

Moving forward, the main priority for the team is to finalize a design and pick one of the three prototypes listed in this report to begin refining and testing. A meeting with the client, Dr. Lerner, is scheduled for next week and at this meeting the update to the shoulder geometry will be decided, from there the team will begin the production of the various components and parts. This meeting is just for choosing the design to make sure that the geometry functions how we need it too, and separate analyses will be performed on the parts to ensure safety. Specific parts on the designs will need to be changed such as the pegs on prototype 3 that hook into the rail system on the shoulder will not be able to withstand the repetitive pressures that will be applied, however, as more of a proof of concept that the geometry will work. Once the final design has been selected and proven safe, we can start testing the limits of our system and start printing the final parts.