FP&L Lower Body Exoskeleton

Spring 2023
Group 1 Authors:

Ford Perry - Electrical Engineering

Moosa Atiya - Electrical Engineering

Kaden Poulter - Electrical Engineering

Thomas Kipping - Computer Engineering

Christopher Oliveira - Electrical Engineering

Sponsor: Florida Power and Light

1 Executive Summary

As years go by with numerous lineworkers working to keep power in Florida's neighborhoods, FPL (Florida Power and Light) has noticed that those lineworkers have developed joint deterioration due to climbing the wooden power poles. Lineworkers are expected to climb poles up to 90 ft high and perform life-threatening work to keep our power grids intact. This is relevant, especially in Florida where we can get hit at any time with a severe hurricane that can knock out power to millions of people's homes. To help that indispensable workforce, FPL has designated our Senior Design team to develop a lower-body exoskeleton that would assist the workers to ascend and descend those power poles to reduce the amount of strain on the muscle and joints of the workers. By providing electrically generated torque at the knee and hip joints we expect to decrease the required human muscle output by a significant portion so that the workers will be able to do their much-needed work without risking their physical health.

Our design will consist of safety features that will allow the user to engage in physical and electronic breaks if needed as well as shut down the whole exoskeleton if the user experiences electrical or mechanical failure in either our equipment or the other pole climbing equipment. Our team has created this document to record our exoskeleton research for both our own tracking and for future teams to be able to add to our design for further iterations. We first discuss our objective with this project as well as the motivation for pursuing this kind of design as well as documenting the other lower body exoskeleton designs out there. Then we document the part selection process as well as the testing involved to justify the parts that we have selected. Afterward, we discuss the design constraints and standards of today's technology before we begin finalizing designs to ensure our design meets today's standards. Then we record all of the design process and testing with a focus on specific detail for all of us to have a record of what we have done and for future teams that can reference our testing for further improvement on our design or another exoskeleton design.

2 Project Summary

This section outlines the motivation and description of the project. FPL has sponsored a mechanical engineering and electrical engineering team to design and fabricate a lower limb exoskeleton. It has been made clear that FPL would like a working prototype by the end of this project. The main purpose of this project is to assist linemen workers who climb power line poles everyday. It is a strenuous task that requires strength and perseverance. FPL is requesting that our lower limb exoskeleton assist the climber without getting in the way, or increasing risk of injury. In fact, our design is meant to increase proper ergonomics, and reduce the risk of injury. Safety is paramount for FPL and so it is for us as well.

2.1 Introduction

Florida Power & Light has noticed a sizable portion of their lineworkers have developed physical health deterioration due to overexertion when climbing wooden power poles. In order to counteract that for the future they have proposed our team create a lower body exoskeleton that will alleviate the strain of climbing wooden power poles. Our design will comprise four motors: two at each knee and another two at each hip. Those motors will be controlled by sensors that can detect when the user moves their legs, both extending and retracting, and communicate to the motors to aid in that movement. The frame of the exoskeleton will be made in a way that there will also be mechanical advantages alongside the electronics. Mechanisms will be implemented in order to absorb the shock of descending a pole to reduce deterioration of the joints, as well as lock the exoskeleton into place on the pole to create a safer work environment.

2.2 Motivation

As residents of Florida, we understand how crucial our lineworkers are to be able to perform their job in a timely manner. After seeing and living in the harsh conditions of the Florida environment, especially with numerous hurricanes, we see those workers operating on numerous power lines to supply power back to millions who lost home or business power due to these hurricanes, or simply throughout the long rainy seasons. In more rural areas that have power lines that don't have space to bring a lift to, the lineworkers have to climb up them themselves.

We have worked closely with the real workers who will be using the exoskeletons and have seen the great danger of climbing these poles. When those workers are required to do that for their careers, they can develop musculoskeletal disorders in their knee and hip joints that can be debilitating to those workers' lives. Studies have shown that 83% of lineworkers reported at least one region of discomfort in either their knee, spine, or hip. These health problems can cause further issues in their professional and personal lives. The workers put their careers and lives on the line every time a power line requires repairs. For those reasons we have deduced that it is imperative for us to develop a way to minimize muscle and joint fatigue in our lineworkers.

2.3 Goals and Project Objectives

Our goal is to create an exoskeleton that will help linemen be able to climb poles more efficiently and experience significantly less strenuous activity on the body when repairing power lines. The goal of the project will be accomplished through the use of multiple motors to help linemen ascend and descend high-powered electrical poles. It shall be made to be cheaper than the other lower-body exoskeletons on the market and be able to be made with COTS (Commercial off-the-shelf) parts.

Another goal is to incorporate either a user interface in some regard that will allow the user to input their weight to modify how the motors will apply force. The user interface will also display information on how much charge is in the batteries and also show if there are any electronic errors and what errors they are. We plan to begin by creating a prototype with a 3D-printed knee joint with a motor attached to it. That prototype will receive input from a sensor to tell the motor to extend or contract the prototype knee. After creating the knee joint we began to incorporate the other three motors into the exoskeleton created by the Mechanical Engineering team.

2.4 Requirements and Specifications

To create an exoskeleton that will help linemen be able to climb poles more efficiently and for it to be less strenuous on the body. It will consist of multiple motors to help linemen ascend and descend high-powered electrical poles. It needs to be cheaper than the other exoskeletons on the market.

Related Standards

These are the related standards to the project. Each standard and its impact will be discussed in Section 4.1.

Microcontroller Libraries
Voltage rating
Current rating
Metal
Batteries

3D Printing
IEEE 1394 - DC Connector Standard
IEC 60130-10 - Serial Communication Standard
Electrostatic Discharge (ESD)

Requirements

Florida Power and Light being our sponsor, has specified many requirements for the successful completion of a working exoskeleton to help linemen with their day-to-day operations. After discussions with Florida Power and Light on what is most important for this exoskeleton, we have come to a conclusion to have seven key deliverables that must be met.

The exoskeleton will be made of a lightweight metal (aluminum) that utilizes four different motors. One on each hip, and one on each knee. There will also be four batteries of the same specifications to power the motors and allow them to run for an adequate amount of time. There will also be a control board system that will be able to show the battery life and other things of that nature. The final part of the exoskeleton will be the implementation of sensors that connect to the control system which then connects to the user’s bodily input to be able to control the motors.

The first deliverable is a locking mechanism. The ability to lock and unlock is vital for the safety of the exoskeleton. It must be able to withstand at least fifty-four Nm (Newton meters) and a minimum of two FOS (Factor Of Safety) The second deliverable would be environmental exposure. Linemen work many extensive hours outdoors in all conditions imaginable. The exoskeleton must be able to withstand all ranges of temperatures varying from zero degrees Fahrenheit to a maximum temperature of one hundred and nine degrees Fahrenheit. Our Sponsor (Florida Power and Light) only services the state of Florida so the range of temperature is biased to Florida's condition.

It will never reach sub-zero temperatures but it does reach over one hundred degrees in the state of Florida. Another weather condition is rain. The exoskeleton must be able to be fully submerged in water for at least thirty seconds. This is a safety measure to make sure that no matter how strong the rain is or if there will be any applications where the exoskeleton will be touching or in the presence of water, the system will not break or shock (possibly injure) the linemen.

The third condition that must be met is a safety system. There is already a locking mechanism condition but now it is imperative to have a way to protect our linemen from falling off the poles. Our plan of action to make sure that never happens is with every lineman that climbs, there is a large rope that wraps around the user's body and the pole in the event they do drop. The rope will latch onto the pole tightly almost instantly and not allow the linemen to descend. It will be able to withstand 50,000 Newtons of impact and not break when falling 36.6 Meters. Also, the linemen will use spiked boots to be able to firmly grasp onto the pole while climbing and descending.

This leads to the next requirement which is condition four, the system shall be comfortable and adjustable. Linemen while working in rough conditions for extended periods of time, we want to make sure they are as comfortable as possible. We did develop a way that the internal temperature will be able to stay between ninety-six degrees and one hundred degrees Fahrenheit. To be able to climb a utility pole requires a wide range of motion, so the exoskeleton will be able to bend up to one hundred and twenty degrees while climbing or descending.

The fifth condition is about minimizing the number of parts the exoskeleton will need while maintaining integrity and safety. It is best practiced to also have it be designed in which the parts are cost-effective and easily replaceable in the event a part needs replacing. The maximum budget will be four thousand five hundred dollars, the entire exoskeleton will be built with a maximum amount of 50 parts and have at least four parts that can be replaced. The sixth condition is flexibility. It is crucial that linemen are able to have as much movement while being safe so the user shall be able to ascend and descend any utility pole, regardless of the obstacle that is in the way. Also, the lineman climbing the utility pole will be able to rotate fully around the pole at any given time.

The final deliverable is the power itself being generated from the motors on the exoskeleton. The system will be able to actively and passively work while providing at least ten Nm (newton meters) torque at the knees and hips while the system is active. This entire project is being funded and created to help reduce the workload and strain that linemen face while working. It is a very labor-intensive job so having two teams of electrical engineers and mechanical engineers gives great exposure to what it means to be an engineer and to solve a real-world problem.

Per FPL and the mechanical engineering team the requirements are listed below:

1. The prototype must be intrinsically safe with no sharp edges, electric hazards, etc.
2. A physical prototype with accompanying user manual and final report.
3. The prototype should be made from fire resistant and non-conductive materials.
4. The full-size prototype should be 13.6 kg. or less.
5. The prototype should focus on the lower body up to the lower back.
6. Create a Safety and Operation procedure, assembly instructions, and product manual.

7. The prototype should be adjustable in size to accommodate various body types.
8. A non-powered or hybrid-powered wearable suit is preferred over a full-powered suit.
9. The target final market cost is $5,000 or less per system.
10. Empirical data analysis completion should be done to demonstrate functionality and use.
11. Create a basic ergonomics analysis/study.
12. Create CAD files for all custom components.
13. All code is to be maintained in a software version control repository.
14. Do a comparison analysis and research into multiple viable concepts.
15. The Final Design Report summarizing project metrics, criteria for success, and results.

Specifications

The system design requires thorough specifications provided through discussions with Florida Power and Light and proper engineering analysis. The specifications listed in Table 2.4.1 are requirements that directly relate to the electrical components of the design. There are a number of other requirements associated with the system design that relate to other parts of the system such as the mechanical design.

The team worked with the sponsor to include Design Requirement 8 to the specifications list. This specification was added to have a way to know the full electrical system was functioning correctly. The specification was an important requirement that was able to be demonstrated to show the functionality of our system.

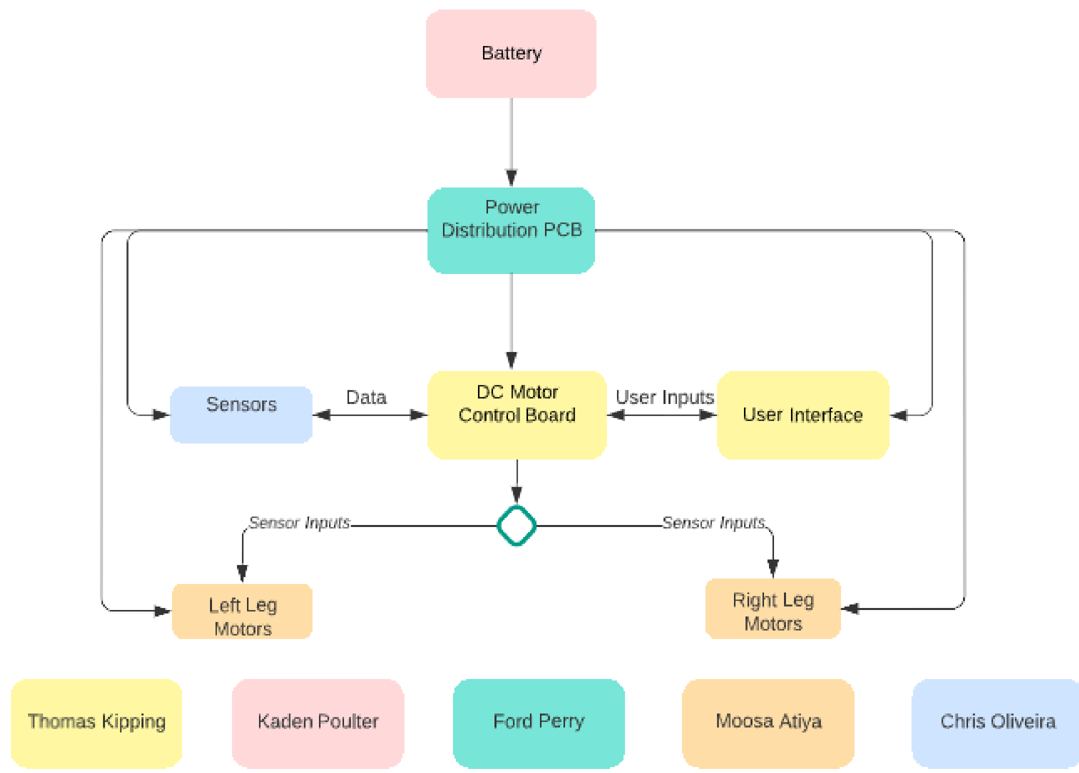
Table 2.4.1: Specifications List

Designation	**Requirement**	**Unit**
DR 1	The system shall have a locking mechanism that can lock and unlock.	≥ 54 Nm ≥ FOS of 2
DR 2	The system shall withstand all necessary environments, ESD, heat, cold water, and fire for one hour.	≥ 0 Fahrenheit ≤ 109 Fahrenheit ≥ 30 seconds in water
DR 3	The system shall have a safety system that will keep the user safe in case of failure or emergency	≤ .5 second reaction ≥ 50000 N impact ≥ 36.6 meters
DR 4	The system shall be a comfortable, adjustable, and practical tool to assist in climbing power line poles.	≤ 100° F ≥ 96° F ≤ 120° of motion
DR 5	The system shall be designed to Minimize the number of parts while Using safe and cost-effective materials that are replaceable when possible.	≤ $4500 ≤ 50 parts total ≥ 4 replaceable parts
DR 6	The system shall be able to ascend and descend a utility pole disregarding any obstacles on the pole.	5.5-inch wide obstacles 360 movements
DR 7	The system shall provide a hybrid active and passive solution to generate torque at the knees and hips to reduce the user's workload and strain.	> 10 Nm active
DR 8	*An electronic system that responds accurately and timely to user movements; sensors respond to angle change in the knee, motors react to the software in a timely manner, and the system recognizes a step.*	*≤ .75 sec*

Hardware/Software Block Diagram

The block diagram provided below shows the necessary steps that we did take to build this exoskeleton. It lays out what connects to what, and how it will all work together. It is also color-coded to show which team member is taking the lead for that specific section, and who is responsible for what.

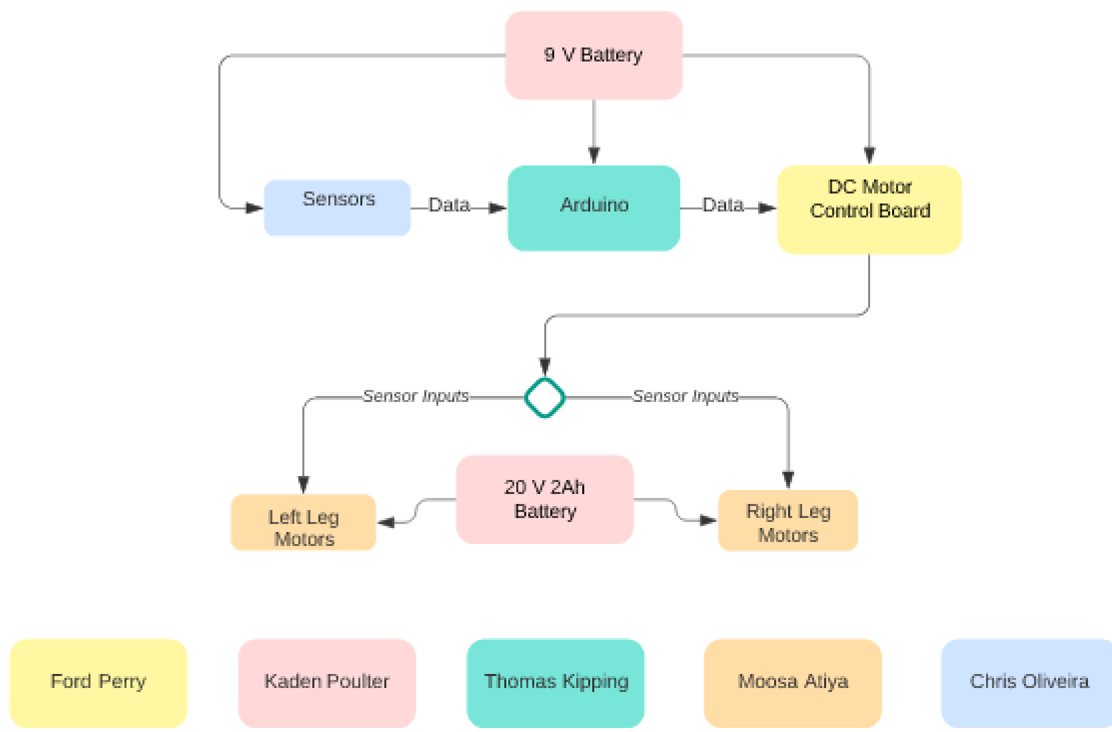
Figure 2.4.2: Hardware/software Block Diagram



There are many crucial steps to properly integrate this into the exoskeleton. It first begins with the battery being able to power the entire build. Not just any battery, we need to make sure that the battery chosen can be strong enough to power needed for the entire build. The battery must also be small enough to be housed properly within the exoskeleton. Then it is important that the battery's power be distributed to all of its vital "organs" such as the motors, sensors, and the UI system.

The control board will then be able to control all of the individual parts and the exoskeleton will be able to work as intended. Every member of this group has an important role that needs to be completed. By everyone having their own section when building this exoskeleton, each member will have their own responsibility and deadlines to report. This is also important for if a team member is unable to complete their part, the other can jump in to support.

Senior Design 2:



In senior design 2 we realized that a few of the components in this diagram had to be changed. We removed the user interface as it was incredibly difficult to incorporate this into our final design. Furthermore, we replaced the PCB with an arduino as we required a much more complex processing system and more processing power. While assembling our design, we realized the 20 volt battery could not be effectively stepped down to power the peripherals. So we incorporated an additional 9 volt battery to power the control system.

2.5 House of Quality Analysis

To create an exoskeleton that will help linemen be able to climb poles more efficiently and for it to be less strenuous on the body. It will consist of multiple motors that will help linemen ascend and descend high-powered electrical poles.

It needs to be cheaper than the other exoskeletons on the market but strong enough to work properly.

There are many requirements that Florida Power and Light have requested, and we are prepared to cover them all. Reading based on our figure below, we did have many things that the company would like to see for when we build the exoskeleton

House of Quality

The house of quality figure below is important as it shows the customer’s requirements and desires. It lists the various different components of the exoskeleton. It also has shown how important it is that it must be done and to be completed properly by Florida Power and Light specifications and also any desires that they may want for the exoskeleton.

The first noticeable importance of our house of quality is submersion. It is absolutely imperative that the exoskeleton is able to be fully submerged and the electronic components not be damaged by any sort of water intrusion. If there was, the water can damage and would harm the electric system. With the suit being metal and the user being surrounded by electrical equipment, it is also quite possible that the user wearing the exoskeleton can be harmed as well if there were some sort of water intrusion so it is important to double check everything and to make sure that there is a zero percent chance that water would ever be an issue.

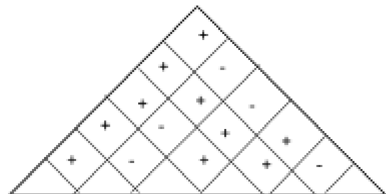
The other engineering requirement that stands out heavily is the ability to easily replace the part and its cost factor. This exoskeleton will be used heavily in very labor-intensive applications so it is also very important that if something was to break or needs replacing, it is easy to find and does not break the bank. The last two major requirements are about the force. It must be able to take a fall of at least 120 feet and an impact of at least fifty thousand N (Newtons) to make sure that none of the components snaps off, potentially endangering the person using it.

Figure 2.5.1: House of Quality Diagram

Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



Category	Weight	Customer Requirements (Explicit and Implicit) / Engineering Requirements	Motors	Control System	Battery Pack	Bungey System	Power Distribution Board	User Interface
		Column #	1	2	3	4	5	6
		Direction of Improvement	▲	▼	◇	◇	◇	▲
Safety	8	Locking Mechanism	●	●	○	▽	▽	▽
	2	Insulated materials	▽	○	●	▽	●	▽
	4	Withstand temperatures between 0 and 109 degre	▽	○	○	○	●	○
	2	ithstand full submersion underwater for 30 second	●	●	●	▽	●	●
	2	Fire Resistant rating	○	○	●	○	○	○
	6	User safety system	○	●	○	○	▽	○
	4	Withstand fall of 120 feet	○	○	○	●	○	●
	4	Withstand impact force of 50000N	○	○	○	●	○	○
	9	Safety Harness	▽	▽	▽	●	▽	▽
	6	Fall resistance mechanism	○	○	▽	●	▽	▽
	8	Manual override system	●	●	●	●	●	○
	5	Adjustable and comfortable	▽	▽	▽	○	▽	▽
	5	Transport system	▽	▽	▽	○	▽	▽
	6	Cheap and Replaceable parts	●	●	●	●	○	●
	6	Storage and tool compartments	▽	▽	▽	▽	▽	▽
	8	Hybrid passive and active	●	●	●	▽	▽	○
		Target	Target for Functional Requirement #1	Target for Functional Requirement #2	Target for Functional Requirement #3	Target for Functional Requirement #4	Target for Functional Requirement #5	Target for Functional Requirement #6
		Max Relationship	9	9	9	9	9	9
		Technical Importance Rating	66	76	74	74	56	52

The last major requirement is the override system. It is key that for every part of the exoskeleton if something was to happen or needed some sort of adjustment, the user will be able to override the system and take control. Climbing the utility poles requires strength and discipline. If, for example, the battery goes out, the burden of holding a locked, twenty-plus pounds exoskeleton could endanger the life of the user. Moving on to requirements that are important but not as major, is the fire resistance.

Working in high temperatures with systems that use batteries and other functions, is important to make sure that it does not overheat or catch on fire. That all components of the exoskeleton must be able to withstand a wide range of temperatures ranging from zero degrees Fahrenheit, all the way to one hundred and nine degrees. The safety of the user will always be of the greatest importance when it comes to choosing and designing the exoskeleton properly. This leads me to my next point which is about insulating materials.

Each individual component will need to be able to be situated on the exoskeleton in a way that they are protected and in some instances, covered. The exoskeleton components, especially the motors must be able to work passively and actively. The ability of the motors to know when to exert force or to slow down is very important in helping the linemen's fatigue and also reducing the strain that the body endures as they climb or descend.

Of high importance is the ergonomics of the overall design of our lower limb exoskeleton. It is a requirement of FPL to have an ergonomic design analysis, and for good reason. The device must be comfortable and easy to use for every user. It must be intuitive, with a small learning curve so that any worker can quickly put the suit on and use it with little turnaround time on learning the device. Additionally, comfort is paramount, and falls under safety.

The exoskeleton will sometimes be used for hours at a time, and the user will be 40 feet above the ground, doing strenuous, dangerous, and sometimes tedious work. All the while, depending on this exoskeleton for assistance in their climb. It is of utmost importance that this user is comfortable so as not to distract them from their work. One misstep is the matter of life and death, and one must be conscious of where all parts of the body, including the exoskeleton, are at all times. Furthermore, ergonomics has to do with the long-term safety and longevity of the worker. Ensuring proper ergonomics mitigates long-term health effects that may injure the user over time.

For this reason, it must be kept in mind the user's posture, and leg placement, so as to not injure or otherwise compromise the user. FPL has also expressed concern about the software in our lower limb exoskeleton. It is a requirement that the code is maintained in a software version control repository. This is important for both the safety and continued use of the product. For one, the code is essential during the working use of our exoskeleton. It will be the controlling factor of all things electronic in our design.

If the code were to fail, the entire power system fails, and this could lead to catastrophic failure of our whole exoskeleton. This could even lead to a malfunction of a motor which could cause injury to the user. The code is maintained as a software control repository enhances the reliability of the code, as well as enabling editing of the code if the end user sees fit. Furthermore, the USB port that will be a part of the design will allow for access to a computer. Updates and edits can then be made to the code from a computer, to upgrade the unit over time.

A weaker yet still important requirement is the storage and tool compartments. The exoskeleton is what some would call a “vessel”, to be an actual extension of the body that will support a linemen’s ability to have extra support and energy to climb and descend utility poles. It is not designed to have “pockets" or areas for storage. Florida Power and Light has opted out from wanting any sort of storage or tool compartment because they don't want to add anything that can possibly be in the way of the linemen. They want the user to have full access to their surroundings and for instance if they are climbing a pole, they don’t want it to be dangerous or impossible for the user to climb “weirdly” or have trouble because there is a storage compartment in an awkward location for them. So the full exoskeleton will be made so that it is smooth to the body and allows for normal function.

The safety harness is very important to the system and its user but it is not that important for the individual components on the exoskeleton. The same can be said about the adjustability and its comfort. The components will be fixed in place and so they are not important when it comes to the requirements. The final condition is its transport system. The exoskeleton will be light enough for an average person to wear and carry but also heavy enough to be able to stand firm when needed and apply enough force to help the linemen do all necessary tasks while working.

2.6 Marketing Requirements

An important aspect when it comes to building this exoskeleton for Florida Power And Light is its actual marketability. Exoskeletons are not common and can not be bought off of shelves so it is important to have some key aspects taken into consideration. Some of these important points are the price, how user-friendly it is, how easy it is to replace any part, and how advertisable it is. The most important is the marketing for Florida Power and Light employees as this technology will be used by them. Working as a lineman that constantly climbs utility poles is considered one of the toughest labor-intensive jobs on the market. It is in the company's (FP&L) best interest to create an exoskeleton that can help relieve some strain for its workers.

A major factor, when it comes to marketability, is the actual price point while building this exoskeleton. Florida Power and Light want this to be a successful project so that they can create hundreds more for their linemen to use. It is in everyone's best interest as well to find the best way to make this as cheaply as possible while keeping its integrity to ensure that nothing breaks and lasts as long as possible. Another factor is how user-friendly it is. An exoskeleton can have many moving parts and it is to be assumed that the consumers will not have a strong technological background. It is assumed they will have limited knowledge of the application and its usage so it is also very important to have the consumers in mind.

The exoskeleton must be easy enough to put on and be able to control. This will make it easier for Florida Power and Light to mass produce and roll out to any one of its employees for any various tasks deemed necessary. The final marketability requirement is actually being able to market only to the company's employees, not anyone else. This project is being entirely sponsored by Florida Power and Light so all information gathered and prototypes built are to be confidential to their company and not for public knowledge. FP&L will have all deciding factors when it comes to information that is made for the public or if it will never be for sale to any consumer outside of its doors.

3 Research and Part Selection

Research into which parts will be used for the lower limb exoskeleton is of utmost importance. Our sponsor, FPL, calls for very specific requirements in terms of safety and design specifications. This being said, we must ensure that every part we purchase meets both our safety and design standards. It is imperative that each part must serve its purpose without fail, to ensure the safety of the user and operation of the device. This section is an overview of the design, parts research, and part selection for the exoskeleton.

3.1 Design Overview

The FPL lower extremity exoskeleton suit will consist of six major components to assist the user in climbing a pole for work on a powerline. The mechanical engineering team has created a CAD design and prototype of the exoskeleton frame in order for the electrical engineering team to integrate all the electronic components into the exoskeleton to develop a fully functional powered lower limb exoskeleton suit. The components include the frame, the motors, the control system, the power distribution system, the user interface, and the battery. The overall weight of our exoskeleton design shall not exceed 13.6 kilograms and must have adjustable dimensions for users of different sizes.

The system's adjustable length dimensions from the sole of the foot to the navel will be between 98.98 and 123.61 centimeters. However, the system is broken into three separate parts: the femur, lower leg, and waist, all adjustable. The femur section will be adjustable from 40 to 50 centimeters and the lower leg from 46.79 to 64.18 centimeters. The waist portion from the top of the femur to the navel will be adjustable between 9.43 and 12.09 centimeters. Furthermore, the unit will allow for adjustments to fit the user's waist in width and depth. The waist adjustment will allow for the difference of a circumference between 65 and 120 centimeters. The ability to adjust the dimensions of the lower limb exoskeleton will make our product highly customizable and ergonomic in design.

Frame

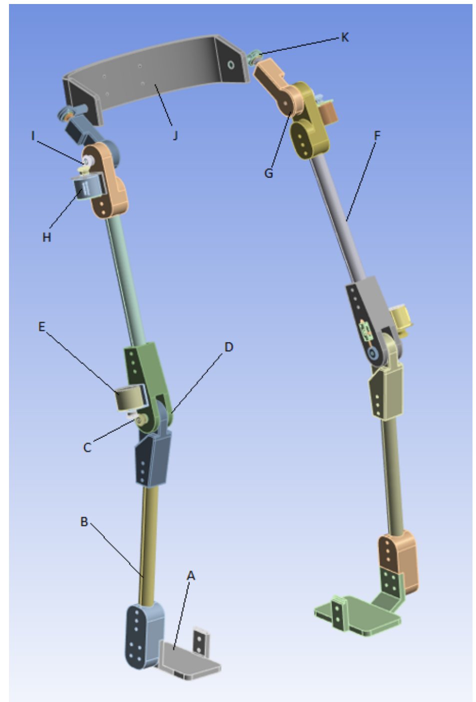


Figure 3.1.1 : Mechanical Team's Computer-Aided Design of Lower Limb Exoskeleton Frame

A: Footrest
B: Shin pole
C: Knee bevel gears
D: Knee joint
E: Knee motor and harness
F: Knee strut
G: Hip joint
H: Hip motor and harness
I: Hip bevel gears
J: Backrest and battery harness
K: Waist joint

The skeleton and backbone of our entire Lower Limb Exoskeleton is the frame that the Mechanical Team has designed. This frame encompasses all supports, joints, harnesses, and attachment points. The struts and joints of the frame will be made of 6061 Aluminum Alloy. The frame makes up the bulk of our design and will therefore account for the bulk of the weight. To mitigate the weight of the frame, the struts will be hollowed out, while maintaining their structural integrity, the weight will be reduced and allow for a passage to safely run our power distribution system.

Furthermore, the 6061 aluminum alloy the frame will be made of was carefully chosen as not only being an economic option but also lightweight and strong. To improve the ergonomics and customizability of the overall lower limb exoskeleton system the adjustable length and width options will be built into the frame. As previously discussed in section 3.1 these adjustments will allow for any user between 160 and 200 cm of weights between 62.2 and 130.3 kilograms. The frame will have multiple attachment points to the user and is pictured above.

The mechanical engineering team considered multiple possible options for the hip, knee and ankle joints. These considerations can be seen below.

“Starting with the **hip joint**, three options were weighted:

Hip Joint Table 3.1.1

Scale: 1 to 5 (5 best, 1 worst)		Hip Joint					
		Hinge		Ball & Socket		Universal	
Criteria	Weight	Rating	*Weighted Rating*	Rating	*Weighted Rating*	Rating	*Weighted Rating*
Complexity	15%	5	0.75	5	0.75	3	0.45
Cost	10%	5	0.5	4	0.4	1	0.1
ROM (Flexion/Extension)	25%	5	1.25	5	1.25	5	1.25
ROM – (Abduction/Adduction)	25%	1	0.25	5	1.25	5	1.25
Rotational motion	10%	1	0.1	5	0.5	5	0.5
Total	100%		3.60		4.60		4.15

The selection of a ball and socket joint was centered around the range of motion offered in two directions, forward of the body and to the side. Since human legs are capable of both directions, as well as small degrees of rotation, ball and socket joints were selected. In addition to the reasons given, a ball and socket was deemed to be the most cost effective, amongst the three joints discussed, relative to the other two. Additionally, a human hip joint is a ball and socket which presents an obvious choice in joint selection.

For the **knee joint**, the selection process was far less complex. Namely, a human knee joint is a simple hinge. Mimicking this action was deemed to be the simplest solution to building our knee joint. The following table essentially is the same as the hip joint table except for the selected joint:

Knee Joint Table 3.1.2

Scale: 1 to 5 (5 best, 1 worst)		Knee Joint					
		Hinge		Ball & Socket		Universal	
Criteria	Weight	Rating	*Weighted Rating*	Rating	*Weighted Rating*	Rating	*Weighted Rating*
Complexity	20%	4	0.8	3	0.6	3	0.45
Cost	15%	5	0.75	4	0.6	1	0.1
Maintenance	30%	5	1.5	3	0.9	5	1.25
ROM (Flexion/Extension)	35%	5	1.75	5	1.75	5	1.25
Total	100%		4.80		3.85	4.15	

An additional consideration for this joint was the deflection. A hinge joint does not allow for lateral, side to side, motion as this motion is counter to the natural motion of a human knee. As with the hip joint, knee joints are natural hinges.

Ankle joints were the final joint that needed to be considered, as this is where human legs terminate. Strong consideration was given to this joint as this is the joint that tends to have the most adverse long-term medical impacts. Linemen tend to develop ankle problems into their careers. After consideration the team decided to proceed with a fixed joint at the ankle.

Ankle Joint Table 3.1.3

Scale: 1 to 5 (5 best, 1 worst)		Ankle Joint			
		Hinge		Fixed	
Criteria	Weight	Rating	*Weighted Rating*	Rating	*Weighted Rating*
Complexity	35%	1.05	0.75	5	1.75
Cost	15%	5	0.75	5	0.75
Maintenance	25%	5	1.25	5	1.25
System Incorporation	30%	3	0.9	5	1.5
Total	100%		3.65		5.25

Starting with the **hip joint**, three options were weighted:

Hip Joint Table 3.1.4

Scale: 1 to 5 (5 best, 1 worst)		Hip Joint					
		Hinge		Ball & Socket		Universal	
Criteria	Weight	Rating	*Weighted Rating*	Rating	*Weighted Rating*	Rating	*Weighted Rating*
Complexity	15%	5	0.75	5	0.75	3	0.45
Cost	10%	5	0.5	4	0.4	1	0.1
ROM (Flexion/Extension)	25%	5	1.25	5	1.25	5	1.25
ROM – (Abduction/Adduction)	25%	1	0.25	5	1.25	5	1.25
Rotational motion	10%	1	0.1	5	0.5	5	0.5
Total	100%		3.60		4.60		4.15

The selection of a ball and socket joint was centered around the range of motion offered in two directions, forward of the body and to the side. Since human legs are capable of both directions, as well as small degrees of rotation, ball and socket joints were selected. In addition to the reasons given, a ball and socket was deemed to be the most cost effective, amongst the three joints discussed, relative to the other two. Additionally, a human hip joint is a ball and socket which presents an obvious choice in joint selection.

For the **knee joint**, the selection process was far less complex. Namely, a human knee joint is a simple hinge. Mimicking this action was deemed to be the simplest solution to building our knee joint. The following table essentially is the same as the hip joint table except for the selected joint:

Knee Joint Analysis Table 3.1.5

Scale: 1 to 5 (5 best, 1 worst)		**Knee Joint**					
		Hinge		**Ball & Socket**		**Universal**	
Criteria	Weight	Rating	*Weighted Rating*	Rating	*Weighted Rating*	Rating	*Weighted Rating*
Complexity	20%	4	0.8	3	0.6	3	0.45
Cost	15%	5	0.75	4	0.6	1	0.1
Maintenance	30%	5	1.5	3	0.9	5	1.25
ROM (Flexion/Extension)	35%	5	1.75	5	1.75	5	1.25
Total	100%		4.80		3.85	4.15	

An additional consideration for this joint was the deflection. A hinge joint does not allow for lateral, side to side, motion as this motion is counter to the natural motion of a human knee. As with the hip joint, knee joints are natural hinges.

Ankle joints were the final joint that needed to be considered, as this is where human legs terminate. Strong consideration was given to this joint as this is the joint that tends to have the most adverse long-term medical impacts. Linemen tend to develop ankle problems into their careers. After consideration the team decided to proceed with a fixed joint at the ankle." Kresl, et al, page 17.

The Table below shows the various weighted ratings and weights.

Ankle Joint Analysis Table 3.1.6

Scale: 1 to 5 (5 best, 1 worst)		Ankle Joint			
		Hinge		Fixed	
Criteria	Weight	Rating	*Weighted Rating*	Rating	*Weighted Rating*
Complexity	35%	1.05	0.75	5	1.75
Cost	15%	5	0.75	5	0.75
Maintenance	25%	5	1.25	5	1.25
System Incorporation	30%	3	0.9	5	1.5
Total	100%		3.65		5.25

Mechanical Locking Mechanism

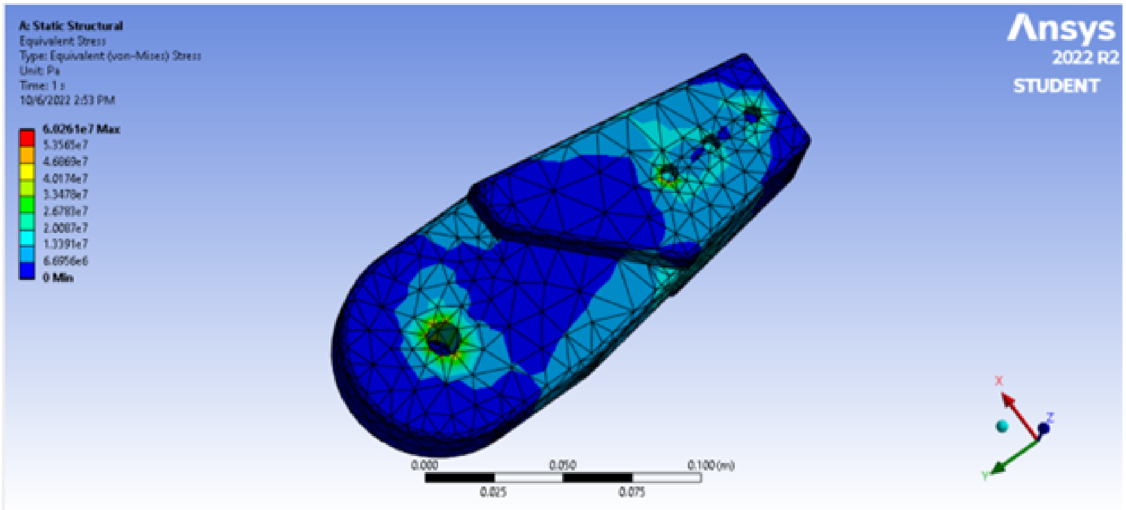
One of our requirements is to incorporate a mechanical locking mechanism within the frame. This must be mechanical to promote safety and provide a failsafe if the electric components fail. This function can also double as a way to lock the exoskeleton into a “sitting” position. This can be beneficial for the user who wishes to do work in a seated position for an extended period of time. This can promote ergonomics as it would take stress off of the user's leg while in this position.

The Mechanical Engineering team has designed a locking mechanism within SOLIDWORKS but has not implemented this into their first prototype. They have done this to avoid any unnecessary meshing with our design of the motor system that we did implement. However, we did use their designed model for the locking mechanism within our design. They broke up the mechanism for simplicity. It will be located on the knee joint and will consist of a locking gear and the motor system that we did implement. Their analysis and specifications of the locking mechanism can be found below.

“**Locking Mechanism**

The system setup for the locking mechanism was broken up for simplicity, while still using a worst-case scenario. The knee joint was positioned at a horizontal locked position, generating the largest moment possible about the central axis, where the locking gear is connected. A force of 1500 N, the user's weight plus the weight of the system, was placed at the holes connecting the upper knee joint and the upper frame rod. The lower connection holes were fixed in place, replicating the lower frame rod and foot in place on the pole.

Figure 3.1.2: Locking Mechanism Stress



The Ansys tests gave the following results:

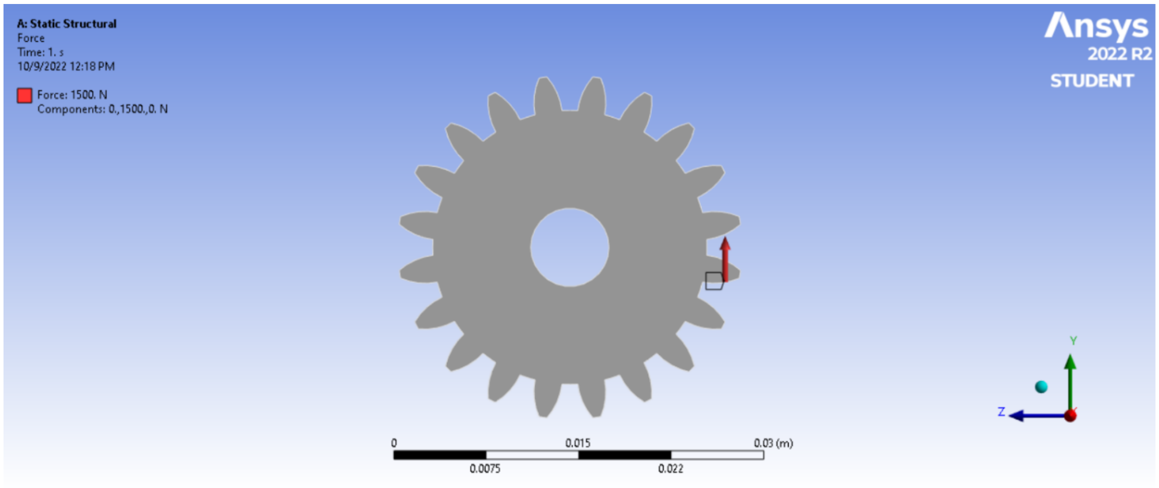
> Maximum Von-Mises's stress: 60.2 MPa
> Maximum deformation: 0.28 mm

The maximum stress appears, as expected, at the axis where the moment will be acting to turn the joint. The stress is within the limits of aluminum 6061, and deformations are small enough to not be noticed by the user or affect the system. Even with compounding deformation from connecting rods, the system will allow for normal motions of the user and still provide the necessary support without being noticeable. It is also worth noting that some of the higher stresses are located at the connecting holes of the upper and lower joint and will need proper bolts to withstand these stresses to keep the system secure.

Locking Gear

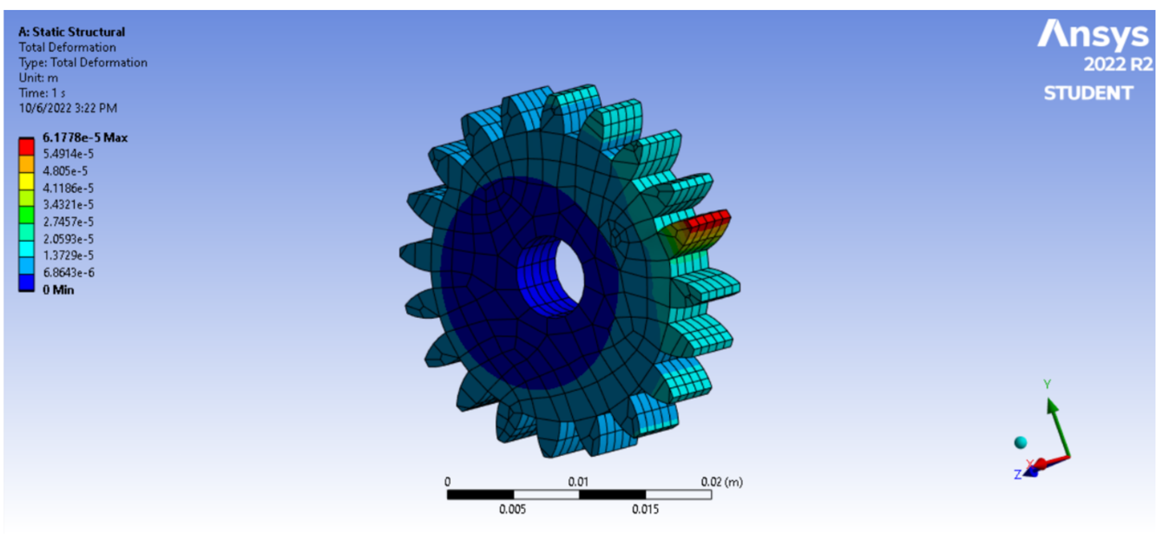
The Table below SHows the Gear that will be used as the locking mechanism for the exoskeleton.

Figure 3.1.3: Locking Mechanism Gear



The gear will stop rotation of the knee joint by way of a barrel bolt assembly sliding into the teeth of the gear. The same weight of 1500 N used on the knee joint is applied to the face of a single tooth to replicate the reactionary force from the pin preventing rotation. The inner face of the gear hole was fixed in place to replicate being bonded to the bar bound to the lower knee connector.

Figure 3.1.4: Locking Mechanism Gear Deformation



The Ansys tests gave the following results:

> Maximum Von-Mises's stress: 114MPa
> Maximum deformation: 6.2 * 10^{-5} mm

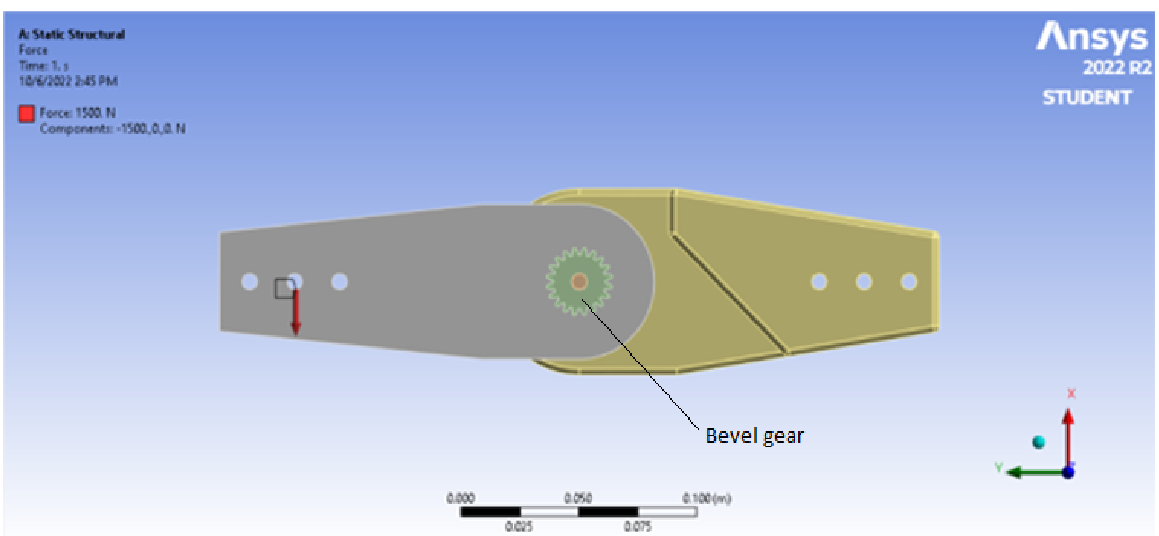
The maximum stress at the base of the gear tooth is within the limit of Aluminum 6061. After testing, it was realized that a more accurate representation of this system would be to put a torque on the inner circular face on the hole and fix a tooth in place by its face. This setup will be explored before ordering the part to ensure aluminum will still be sufficient as material for the gear." Kresl, et al, page 37-38.

Motor

The motor serves a very important function in our lower limb exoskeleton design. With 4 motors, at both hip and knee joints, this will be the source of all the power to assist the climber.

The figure shown below describes either the hip or knee joint in depth on how it will function and move.

Figure 3.1.5: Either hip or knee joint with fixed bevel gear attached



The hip and joint motors are the essential components of our exoskeleton design. These motors will be delivering all of the power and are of utmost importance when assisting the climber. Located at both the hip and knee joints the hip and knee motor will be turning opposite one another to maximize the force in the downward direction.

The bevel gear attached to the joint shown above will be the access point for the motor to engage with the frame and torque it once the motors are given the signal to be powered on. Due to electrical and weight constraints, the goal of our lower limb exoskeleton is to assist the lineman user with about 20% of the power they use with each upward step they take. The user usually needs about 93.525 Nm of torque at each hip and 108.489 Nm at each knee. The exoskeleton's goal is to provide about 18.705 and 21.698 Nm of torque at each hip and knee respectively.

To achieve this goal we need to maximize the amount of torque each motor produces by obtaining the most efficient motors with high kV ratings. The higher the kV rating, the higher the torque the motor can produce. However, it is important to keep in mind both our weight and electrical limitations. The maximum weight of our exoskeleton design must be no more than 13.6 Kilograms and our motors must not be too demanding on our battery. To further help maximize our torque output the mechanical team will be finding the best gear ratio to boost torque.

Passive Motion Assistance

The Mechanical engineering team would also like to include a passive motion assistance to the design. This will be implemented to aid the user by maintaining ergonomics and further assisting the user by adding to the torque and power involved with moving the joints. This passive system will lighten the load for the user by taking away from the force they must exert to climb up the pole. The mechanical engineering teams analysis and consideration is show below:

"**Unpowered motion assistance**,

being a key component in this design, was considered with a heavy emphasis. This exoskeleton being a hybrid both powered and unpowered methods of assistance were considered. For unpowered assistance, four options were considered:

Passive Motion Assistance Table 3.1.7

Scale: 1 to 5 (5 best, 1 worst)		Motion Assistance (Un-powered)							
		Bungie		Pulley		Eccentric Pulley		Spring	
Criteria	Weight	Rating	*Weighted Rating*	Rating	*Weighted Rating*	Rating	*Weighted Rating*	Rating	*Weighted Rating*
Force-to-Weight	20%	2	0.4	4	0.8	3	0.6	2	0.4
Reliability	20%	5	1	4	0.8	3	0.6	4	0.8
Weight	15%	4	0.6	2	0.3	2	0.3	3	0.45
Complexity	15%	5	0.75	3	0.45	2	0.3	4	0.6
Max Force (Torque)	25%	2	0.5	3	0.75	3	0.75	2	0.5
Cost	5%	5	0.25	4	0.2	4	0.2	4	0.2
Total	100%		3.5		3.3		2.75		2.95

The team were given several exoskeletons to test, which were provided by FPL. Emphasizing force-to-weight, reliability, and max-force we decided a bungie would be the most beneficial to our design. Additionally, the exoskeletons provided to the team were worn and tested.

Bungies provided the most consistent force throughout the range of motion they provided. Bungies are also excellent at maintaining force while operating outside of their intended range of motion. If a joint is moved outside of the intended range or, for example, a ball and socket joint is used, bungies still provide consistent force through all degrees and angles that a ball and socket can achieve. Consistency was the main driver in the selection of a bungee for unpowered assistance." Kresl, et al, page 19.

Tubing

An important part to consider when discussing the frame of the exoskeleton is the metal tubing that will connect the hip joint to the knee joint. As well as another metal tubing that will connect the knee joint to the foot component. The material that the tubing will be composed of is Aluminum 6061. The major aspect of the tubing that needed to be considered is the optimal size and dimensions. Using four different types of tubing, the MAE team composed a series of tests to determine which type of tubing would be best to use.

Rod Deformation Table 3.1.8

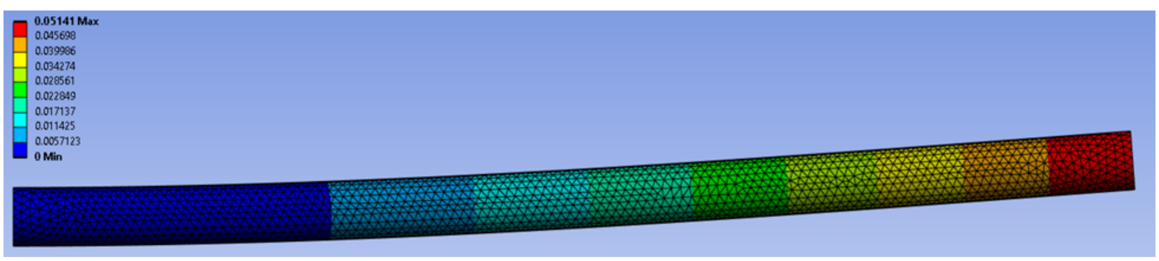
Inner Diameter	Outer Diamter	Wall Thickness	Max Deformation (m)	Max Stress (MPa)	Max Strain (m/m)
1.25	1.12	0.065	0.85465	754.2	0.010924
1.25	1	0.125	0.05141	449.34	0.0065085
1.25	0.875	0.1875	0.039915	346.78	0.0050229
1.25	0.75	0.25	0.03483	328	0.0047514

The outer dimension was kept steady at 1.25 inches to ensure it would fit in the holes designed in the joints. The inner dimension was the variable in these tests to understand how thick the tubing needs to be. The tests measured the max deformation, max stress, and max strain. The max deformation describes how much the component can bend before the component is broken. Max stress describes how much force can be placed on a component before it is compromised.

Max strain describes how much strain can be placed on the tubing before it is compromised. “In this test, the maximum stress for all the models is above both the tensile yield strength, at 276 MPa, and ultimate tensile strength, at 310 MPa, of Aluminum 6061 [1]. This is concerning since this means that if this situation happens to the model, it will cause damage to the exoskeleton and possibly harm the climber. To resolve this, we must prevent this situation from happening so that the forces on the pole are not as substantial.

Firstly, we chose the tubing with a wall thickness of 0.25 inches which had the least difference from the yield strength. Another factor that must be considered is that the pole should never be in a completely horizontal position holding the full weight of the climber and the exoskeleton. This can be accomplished by ensuring that the belt be attached to the pole at all times when the system is stationary. This can avoid a situation where the tubing is damaged.” Kresl, et al, page 23.

Rod Table 3.1.9



Control System

The purpose of this exoskeleton is to assist with climbing. That being said, the motors shall only be engaged when assisting with one direction, this being down, or straightening the leg from a 90-degree position. The design of the exoskeleton allows for a failsafe to ensure no over-torquing of the user's leg, however, the control system is still crucial. The control system consists of a RaspberryPi, a variety of sensors, and the required wiring network to send the signals.

The control board will be programmed to ensure the motors are engaged only when they are needed. The sensors will send a signal to the control board once the user has initiated an upward movement by pushing down with his/her leg. The RaspberryPi will then relay this signal down to the hip and knee motors to engage and help thrust the user up.

In addition to this, we did also use the RaspberryPi to interact with our battery and user interface. The RaspberryPi will be responsible for relaying the battery life to the user and storing necessary information input by the user. The control system is the brains of our entire Lower Limb Exoskeleton and therefore must not be compromised. The overall architecture of our control system will entirely be reliant on the signal produced by the sensors. Once the sensor has been engaged, a signal will be relayed to the RaspberryPi which will be coded to engage the motors at the right time and in the right direction.

Power Distribution System

Using a specially designed PCB and a network of wires, power will be distributed accurately and efficiently to all demanding components. Headed with the battery the entire system will run down the legs from the back of the frame through the hips and down to the knees. This system will be integral in the operation of the lower limb skeleton and must not be compromised. For this reason, wires will be run through the interior of the skeletal frame, and the power distribution PCB will be held within the battery harness. The control system, user interface, sensors, and motors will all rely on the power distribution system to be fully functional to avoid catastrophic failure. We used copper wires that must be capable of carrying enough voltage to engage our motors at the desired power level.

User Interface

The user interface will be the access point for the user to interact with and gather information from the exoskeleton. The device will have both Bluetooth and a USB port to access the user interface. To further increase the customizability of the system and overall compatibility with the user. The user interface will allow the user to adjust settings, such as power output based on weight and size, and update the software as needed. In addition to the USB access and Bluetooth capabilities, the exoskeleton will also feature a few other interactive components.

Located on the backplate, on the outside of the battery pack, multiple LEDs will display the battery life. Located next to the LEDs will be an on/off switch for the entire exoskeleton. For safety reasons a beep will sound once the battery has been depleted to 25%.

Battery

On the back of the backplate, the battery will be enclosed in a removable battery pack. The battery pack is removable to allow for charging and a quick way to swap batteries to get the exoskeleton back in operation without having to wait for a charge. The most important part of the exoskeleton is arguably the battery. This is why the battery will be to IEEE 1394 standards and be protected by the battery pack housing. Our battery requires at least an hour of continuous operation and must provide enough power to the motors to ensure 20% of the user's force is being compensated for. This means we need to maximize our AmpHours and have a minimum of 20 volts. After research, we intend on combining two batteries in parallel to amplify the amperes and maintain the voltage of the batteries. The three types of batteries that are being tested and considered for the power source: are lithium-ion, lithium polymer battery, and nickel-cadmium.

3.2 Existing Products

While there are other exoskeleton systems, particularly, lower limb exoskeletons, there are none that have been specifically designed for our application. FPL has tasked our senior design team with designing and prototyping a lower limb exoskeleton specifically to assist linemen with climbing wooden poles for power lines. This brings up many important aspects in terms of design limitations and safety concerns. Being of utmost importance, our highest value as a team is safety, the safety of the user comes at the forefront of our entire thought process. To ensure safety we think about ergonomics, failure points, weight limitations, and possible faults in our electronics.

Furthermore, our design must be lightweight, slim, and easy to use. Lineman climbers have been doing the job for decades without the assistance of an exoskeleton, our goal is to help the climber, without burdening them in any way. The system will be simple and offer assistance on the ascent of the climb. To get an idea of what pre-existing exoskeletons can change or improve upon we did analyze competitors on multiple different categories. Safety, ease of use, ergonomics, electronics, and overall design. It is important to keep in mind that these competitors have designed their exoskeletons for different applications than ours, however, we can learn from these technologies just the same.

SuitX - LegX

The LegX product manufactured by SuitX out of Emeryville California is a top-of-the-line product with a price tag of nearly five thousand dollars. Designed to reduce stress on the user's legs while in a kneeling or squatting position. The design is knee focused and reduces muscle strain on the quadriceps around the knee joint while squatting or kneeling for prolonged periods of time. The use case of SuitX’s LegX product is for below-hip height panels and factory work. SuitX has taken into account the safety of the user by significantly reducing the stress and strain of working while in a kneeling or squatting position. It has been proven to reduce stress on the rectus femoris with a 22-56% median reduction of activity in that muscle group.

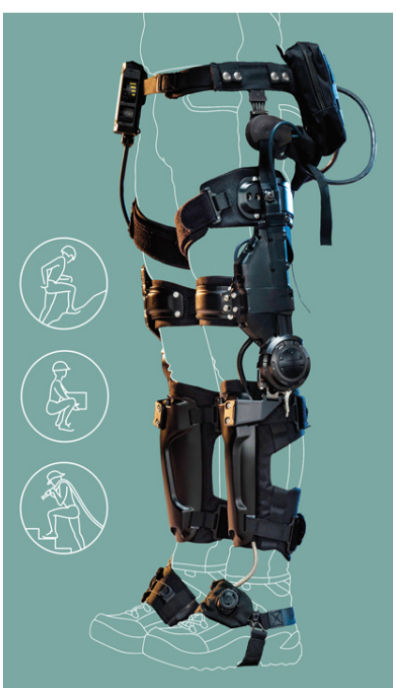
Figure 3.2.1

As far as safety failsafe go, SuitX has not made it clear whether or not their product has many. Hyperextension of the knee is of the greatest concern, and it is otherwise not stated on their website if there is an electronic or mechanical mechanism preventing this from occurring. Furthermore, the website states nothing about the battery life or alarming mechanism for whether or not it will alert the user that it will die soon. However, the product seems incredibly easy to use and has a very ergonomic design. The system has a slim profile and sits off to the user's sides, enabling a full range of motion and natural movement while still being assisted with most activities. SuitX advertises the device to have an intelligent electronic system that recognizes normal walking and stair climbing versus strenuous squatting while at work. This enables the user to have complete natural and fluid movement while walking and the system will engage once it recognizes a squat or kneeling position. This will transfer the user's weight from the knee to the device and into the ground. The other mode that LegX is capable of is the locking mode, which essentially turns the exoskeleton into a chair that the user can rely on to hold their weight.

The overall design of this product is ergonomic, low profile, and well-made. However, the LegX product is not satisfactory for our purposes. Safety is not a focus of this product and it seems to be made for groundwork, not for climbing.

Lockheed Martin - Onyx
Onyx is a lower limb exoskeleton designed and manufactured by Lockheed Martin. This product is specifically designed to lower the strain induced by knee-intensive activities. Onyx has been proven to reduce the electromyography response of the user's knee joints and leg muscles by up to 90%. Their mission is to enhance the endurance of the user so that soldiers in the field can last longer while on strenuous treks with a large load to carry.

Figure 3.2.2: Lockheed Martin Suit



Onyx successfully reduces the load on the knee without adding much weight onto the soldier's entire kit. Keeping safety at the forefront of the design, Lockheed Martin has included sensory equipment that will keep track of each user's vitals and report them in real-time. Lockheed Martin admits that this product is not yet complete and there is still work to be done to further enhance the ergonomics and safety while lowering the complexity of the product. Being sleek in design, Onyx is incredibly ergonomic aside from a few cables that are prone to be snagged.

The suit itself enables the user to have fluid, natural movement, while considerably lightening the load. They state that the overall performance of a soldier wearing the Onyx system is improved by about 25%. This product also showcases a predictive AI that once it learns the user's movement, will accurately predict the user's next move. This advanced electronic system will enable the Onyx Exoskeleton to send torque to the correct joints with accurate timing, enabling completely natural movement. The design of Onyx is very lean, weighing in at less than 20 pounds. Making Onyx incredibly versatile with tons of options at such a low weight. This low of a weight can be attributed to the materials in use: aluminum, carbon fiber, plastic, and titanium, all incredibly lightweight but strong materials.

The downsides to the complex design of the Onyx lower limb exoskeleton are the multiple parts, attachment points, cables, and the fact that it is not yet ready for many of the environmental factors that it will experience in the field. Overall, Onyx is an easy-to-use and lightweight product that is not very cumbersome. The only challenges of the design that would hinder the safety of a lineman climber would be the cables connecting several of the different parts. These cables are exposed and extrude from the rest of the system, these are prone to be snagged if not severed, which could pose high health and safety concerns. Furthermore, Onyx is not yet waterproof or ready to see the vibration, dust, and sand, or shock, making it hard to employ this for real use. While this product is incredibly advanced, it can be assumed it carries a very high price tag and is not practical for the purposes of our project.

ReWalk - Personal 6.0

The Personal 6.0, designed and manufactured by ReWalk, is a lower limb exoskeleton made to assist patients who have lost the ability to walk. The sole purpose of this lower limb exoskeleton is rehabilitation therapy. This product helps users who might experience pain while walking or who otherwise could not walk at all. Designed to take the weight off of the user's back and knees, Personal 6.0 by ReWalk is entirely focused on the safety and well-being of the user. Using only subtle movements based on shifts in the user's center of gravity, the design does not allow for injury to the user. Furthermore, the average users of ReWalk products are not used to standing on their own so rewalk provides crutches specifically designed to help the user learn to walk again, and keep their balance.

Figure 3.2.3: ReWalk: Personal 6.0 Suit

Seeing how this is a product designed for rehabilitation patients, it must be incredibly easy to use, mount, and dismount. It appears that for a patient to be using this by themselves, it would be quite challenging to put on and get up due to their own mobility constraints. However, the user will generally be under the supervision of a clinician and this is to be expected. Ergonomically, the device serves its purpose. Despite it being quite bulky on the side and back, the ReWalk Personal 6.0 does appear to be very user-friendly and ergonomic in movement. This system has 6 degrees of freedom, 4 of which are electronically actuated, with one motor at each hip and knee. Furthermore, the device has a user interface located on the forearm of the user, allowing the user to select between multiple predefined motion profiles. Another feature that the ReWalk possesses is the ability to have software updates, to improve the product as the company releases updates.

Overall, the ReWalk Personal 6.0 has a very specific and niche use. The bulky design, slow-paced movement profile, and motion based on the user's center of gravity lend itself very well towards the rehabilitation space. However, for working people, who need to move fast, be agile, and move irregularly, this product is not for them. We can appreciate the use case and architecture of the design, however there is not much we can take away from this specific product.

Ekso Bionics - EksoNR

This lower limb exoskeleton designed and manufactured by Ekso Bionics is another rehabilitative device. EksoNR was designed to assist paraplegic patients who have lost the ability to walk. Their goal is to reach people who have been paralyzed for the rest of their life and get them back on their feet. This device can even help people who have recently lost the ability to walk to regain muscle memory much faster and even get them totally self-dependent.

Being a system designed for the healthcare industry, safety is Ekso Bionics' number one priority with the EksoNR. Featuring postural support, clinician control, and an FDA clearance for multiple sclerosis, EksoNR could be the safest lower limb exoskeleton to use. The posture support ensures the user's healthy ergonomics and correct posture for spinal health. Clinician control not only allows the rehabilitator to set goals and gait for the patient but also is there to ensure the safety of the user. The FDA has even approved this product to help

Figure 3.2.4: Ekso Bionics: EksoNR

patients who suffer from Multiple Sclerosis, meaning it has passed many safety standards in order to achieve this clearance. Furthermore, the EksoNR is extremely easy to use, designed to be put on and used by patients who suffer from paralysis. Ergonomically, this product is perfect for its purpose, with a posture corrector on the back and a sleek, non-bulky design, the system is out of the way and is only there to assist.

Despite being on the heavier side, 60 pounds, the exoskeleton is designed so the patient only bears their own weight. The dimensions are even adjustable for users of all sizes as well as software that quickly adapts to the user to maximize compatibility and rehabilitation.

The cutting-edge electronics and software are what really make the EksoNR stand out among the competition for rehabilitative lower limb exoskeletons. Data capture, artificial intelligence, and an interface for doctors to customize targets and constraints based on the patient. All of the electronics enable this device to be extremely adaptable and be used from patient to patient.

Additionally, the electronics promote safety by relaying important information about the user's gait and using statistics. The artificial intelligence “Smartassist Software" enables customization of motor support for various impairment levels and is completely user-dependent. AI will even monitor the user's gait and promote correct form while walking by minimizing compensatory gait patterns.

This design consists of 6 degrees of freedom, 4 of which are actuated, at both the hip and knees, leaving the last at the ankles passive. Powered by two sets of long-lasting rechargeable Lithium Ion batteries, the EksoNR can be used continuously for hours. Made of carbon fiber, aircraft aluminum, and hand-sewn fabric for comfort, the EksoNR weighs in at 60 pounds. For purposes of rehabilitation, this system is perfect for the medical space, however, for our purposes, the EksoNR is far too cumbersome, heavy, and not powerful enough. This device is designed to allow the user to walk like a normal person, not assist and power climb or other working movements.

REX Bionics - REX

The company, REX Bionics has developed a lower body exoskeleton suit, REX, that is designed for the purpose of providing robot-assisted physiotherapy to rehabilitate people with mobility impairments. What sets REX apart from the rest of the competition is the capability of keeping the user balanced and hands-free without the need for supplementary support, regardless if the user is walking, standing, turning, or even exercising. Additionally, unlike most exoskeleton suits that require excessive time to be

Figure 3.2.5: Rex Bionics: REX

adjusted and equipped onto the user, REX takes about five minutes before the user is ready to operate the exoskeleton. REX was made with the consideration of being universal in terms of being functional for a wide range of people with different body physiques and mobility disabilities.

To accommodate for a person's height the legs of the exoskeleton can be shortened or extended to fit people that are between 1.42 meters to 1.93 meters in height. Furthermore, the user is also secured into the suit by an abdomen strap, leg cuffs, and a harness that are all adjustable to ensure the user is safely and comfortably locked in. The exoskeleton frame was built using a polymer material known as carbon fiber. The reason this material was chosen is due to the material having a very high strength-to-weight ratio, which allocates the benefits of the exoskeleton being exceptionally lightweight, 86 pounds or 39 kilograms, and stable. The superior stability of the exoskeleton comes from the uniquely designed positioning control system that comprises 27 microprocessors that are controlling all the actuators. REX is also suited with ten specially designed DC linear actuator motors that are distributed evenly along the hip, knee, and ankle of each leg to provide substantial power for supporting the movement of the user.
The high-quality material used for the frame and abundant motors allow a person weighing up to 220 pounds or 100 kilograms to operate the exoskeleton. The motors are powered by lithium-polymer batteries rated at 29.6 volts and 16.5 amp-hours and can hold a charge for about one hour. The battery can be interchanged with another battery for an extended hour of use, as well as recharged to full capacity in 90 minutes.

Indego - Indego

Indego Personal is a lower extremity-powered exoskeleton suit that assists individuals with movement impairments. The suit is considerably light as it only weighs 29 pounds or 13 kilograms. The height and width of the exoskeleton can be altered to be accessible for many people, as well as to ensure the user is secured and comfortable when equipped with the suit. The suit is not worn like a backpack and does not have any upper body components in the design, that way the suit can be equipped while seated in a standard wheelchair. Additionally, the exoskeleton features a sectional design consisting of five parts that can be easily equipped and equipped by the user without the need for assistance. The benefit of this feature is that it provides an opportunity for people to utilize the exoskeleton

Figure 3.2.6: Indigo: Indigo Suit

independently. The exoskeleton has 2 degrees of freedom sections that are composed of two DC actuated motors located at the hip and knee joints of the exoskeleton suit.

The motors are also connected to sensors that are embedded in the control system. The electronic components are powered by a lithium-ion battery that is located at the hip section of the exoskeleton. The way that the user operates and moves the suit is via posture differences recognized by LED and vibrating signals: (A) direct the device to stop or standstill by maintaining an upright posture, (B) lean forward while wearing the device and it will assist you to stand up and walk, and (C) lean backward for the device to help you sit. There is also an application that was developed to allow additional control over an individual's gait parameters which shows: (A) stride length, (B) step frequency, (C) step height, and (D) records walking data so that users can track their progress. This allows gait-impaired people to keep track of how the device is helping them be able to stand and move again.

3.3 Part Research

The electrical engineering team is responsible for researching, selecting, and purchasing all electronic components required to make the exoskeleton fully functional.

Frame

The mechanical engineering team is responsible for the design and fabrication of the frame. Being the backbone and structure of the entire lower limb exoskeleton, the frame must be adjustable, reliable, durable, and lightweight, but able to withstand considerable forces. The frame is more than just the skeleton of the exoskeleton, it also is the component that harbors all of our degrees of freedom. It will also be the structure on which all other components are dependent on to house and protect them.

This means the frame will need to be designed in a way to keep all components out of the way of the user but also easy to access for maintenance or customization. As a part of the frame, we did utilize latches to extend or shorten the upper leg, and lower leg portions to fit the user. Furthermore, the waist portion can be adjusted to accommodate people of all waist sizes. The mechanical team has analyzed the frame they have designed for different modes of failure and has multiple fail safes in place to mitigate any losses.

FPL has left us with strict requirements for safety, ergonomics, and dimensions. Being that the frame comprises the majority of the exoskeleton, this is the component that must be focused on the most when considering weight and size limitations. Our complete exoskeleton must weigh less than 13.6 kilograms and accommodate people who are between 156.4 and 187.4 centimeters tall and weight range between 62.2 and 130.3 kilograms.

Keeping this in mind, it is imperative to use the lightest material possible to maximize portability and reduce strain on the individual who is wearing the exoskeleton. While it is important to have the device as light as possible, it is more important to ensure the frame can withstand high-impact forces, in case of any falls or hitting things under normal use. To maximize the durability and minimize the weight of the exoskeleton the two most important things to keep in mind are design and material used.

Materials

The main material being used is 6061 Aluminum Alloy for all structural components. For housing, we did use 3D-printed plastic and fabric where needed. There were several other materials that were considered for the main frame such as carbon fiber, fiberglass, plastic, and steel alloys. Many of our competitors utilize carbon in their design, as it is lightweight and can withstand large forces. However, it is important to keep in mind our budget and weight limit with all of these materials because both are equally important.

The table shown below breaks down every material in which was considered being used for the frame. Showing a comparison which goes into tensile strength, moment of elasticity, yield strength, density, and price per pound. All of this information was found by looking through scientific properties of each material and finding quotes for parts we would need online.

It is apparent that the strongest material by far is carbon fiber. With a tensile strength and yield strength of 3500 MPa, carbon fiber surely is the most durable material of the four. Even the moment of elasticity is 228 GPa, 28 GPa over the next hardest to deform, steel. Fiberglass is the second in the running of strength, with 3310 MPa of tensile strength, and 207 MPa of yield strength. These two fibers are also the lightest to use, with only 2 g/cm3 and 2.44 g/cm3 respectively. However, these are by far the most expensive materials at $10 and $3 for carbon fiber and fiberglass respectively.

Looking at the metals, the strengths are far less, however, these materials are a lot cheaper. Steel is 420 MPa and aluminum 6061 is 207 MPa for their tensile strength. Steel's moment of elasticity is 200 GPa, making it far harder to deform than the 70 GPa moment of elasticity of aluminum 6061. Aluminums strongest attribute is its density, being the lightest metal of the two at 2.7 g/cm3 whereas steel weighs in at 7.85 g/cm3. The price per pound of aluminum is only $0.5 making it the most affordable of the materials as well as the lightest.

We decided that aluminum was the best material to go with because of the cheap price point as well as the similar properties to steel. Furthermore, this material is the easiest to order and get custom made. Carbon fiber and fiberglass had an exponential increase in price when custom ordering a specific part. This is due to the complex process it takes to fabricate parts in a specific way. Steel is also expensive to custom order, and does not provide many benefits over aluminum. Therefore, aluminum is the most logical choice out of all four materials.

The table below describes the comparison between all the materials that we considered for building the exoskeleton.

Table 3.3.1: Material Comparison

Material Comparison				
	Carbon Fiber	**FiberGlass**	**Steel**	**6061 Aluminum alloy**
Tensile strength of Material	3500 MPa	3310 MPa	420 MPa	207 MPa
Moment of elasticity	228 GPa	72.4 GPa	200 GPa	70 GPa
Yield strength of the given material	3500 MPa	207 MPa	240 MPa	241 MPa
Density at grams per centimeters cubed	2 g/cm3	2.44 g/cm3	7.85 g/cm3	2.7 g/cm3

Price per pound	$10	$3	$0.3	$0.5

For senior design 2, We ended up using carbon fiber. We found an affordable supplier with a size that we could use.

Carbon Fiber

Carbon fiber is the most logical material to use when considering the construction of an exoskeleton. It is an extremely lightweight material with an incredibly high specific strength. With a general density of 1.75 grams per cubic centimeter and a specific strength of over 2400 kilonewton meters per kilogram. As well as a very high modulus of elasticity at 200 to 500 GigaPascals and 1 to 3 GigaPascal compressive strength. These attributes of carbon fiber make it incredibly hard to deform, especially with any force that we are expecting the exoskeleton to go through.

The high strength combined with the low density makes carbon fiber by far a much lighter and stronger option than any metal alloy. However, carbon fiber is considered a more expensive option, pricing in around $227 for a single tube that is an inch thick and 80 inches long. Furthermore, any carbon we would want to use in our lower limb exoskeleton would need to be manufactured to our exact specifications. This will further increase costs, not to mention the lead time of manufacturing something like this.

Carbon fiber is not easy to work with and requires special machinery to fabricate or meld to a specific shape, which could bring us beyond the scope of our project. Lastly, while safety is paramount in our lower limb exoskeleton, it is important to note that carbon fiber is not fireproof. Since the user will be working with high voltage equipment, and our device itself is powered, there is a lot of risk for high temperature and potential fires. For this reason, carbon fiber is not optimal for the purposes of our project.

Fiberglass

Fiberglass is another manufactured material that would lend itself quite well for the purposes of an exoskeleton. It is a lightweight, durable material that is commonly used in performance situations. With a specific strength of 1,300 kilonewton-meters per kilogram, fiberglass is far superior to aluminum and steel. However, it is important to keep in mind how dense steel and aluminum are, which account for the lower specific strength. The general density of fiberglass is 2.44 grams per cubic centimeter, making it lighter than carbon fiber and other metal alloys.

However, as we look into more properties of fiberglass, it is apparent that it is not well suited for our purposes. The modulus of elasticity is only 72.4 Gigapascals, meaning it will be much easier to deform and bend the lower limb exoskeleton than carbon fiber. Furthermore, it is also another expensive material. Being a material that must be custom made to our desired specifications by a fabrication company. It will cost more than just the material, but also the cost of labor and fabrication. A single fiberglass tube, that is not to our desired dimensions, costs $43. Not to mention the lead time on a product that needs to be built to order. Due to overall practicality, cost, and availability, we decided not to go with fiberglass.

Plastic

While it is light, plastic is a brittle material, with a low melting point, and is not fireproof. For the bulk of our frame plastic is not a feasible material to use. It will not be able to withstand the forces of just daily walking, reliably, or for very long. At the knee joint we are expecting moments of torque of 22 newton meters and at the hips 20 newton meters. Furthermore, the force pushing down on the foot harness of the frame is expected to reach 1557.6 newtons.

The maximum amount of deformation our lower limb exoskeleton will be allowed to reach is 0.465 millimeters, at 37.45 MegaPascals. With the typical polypropylene, nylon, high-density polyethylene, and polyvinyl chloride having a typical yield strength between 12-55 MPa. Even ABS filament, commonly used for 3D printing, only reaches a strength of 75 MPa. This is far less than the yield strength of fiberglass, carbon fiber, steel, and aluminum. Making plastic too risky an option to have any structural purpose.

However, plastic can still have a purpose in our design. We did use ABS filament for various components along the frame that do not have any expected forces being applied to them. The battery housing located on the backplate will be a 3D-printed, box-like structure that holds the battery pack. The housing will be attached to the backplate, but the battery pack itself is meant to be easy to remove and replace. Furthermore, each of the motor housings will be 3D printed structures, that conceal and protect each motor, from environmental factors and minor bumps. ABS filament is the plastic of choice due to it being readily available and able to be quickly fabricated into any shape and design of our choosing.

Steel

Metal alloys are by far the most reliable option when considering a strong, fireproof, and lightweight material. Unfortunately, steel is not the lightest metal alloy, but it is incredibly durable. With a tensile and yield strength of 420 and 350 Megapascals respectively, this is far stronger than the expected forces to be applied to the frame. Even the modulus of elasticity at 200 GigaPascals, far exceeds the expected shear stress of 20.78 MegaPascals. This makes steel a smart choice for our purposes as max deformation can only reach 0.465

millimeters. Despite its high strength, steel is a very dense and heavy metal. At 7.85 grams per cubic centimeter, it is nearly quadruple the weight of aluminum alloys. This being said, steel is not an ideal choice to be used for the bulk of our frame. We are arranging to have the lower limb exoskeleton be as light as possible.

6061 Aluminum Alloy

6061 aluminum alloy is the material of choice for the structural components of our frame. Aluminum is a strong lightweight and cheap material that is easy to work with. Weighing only 2.7 grams per cubic centimeter, it is one of the lightest metal alloys that we can get our hands on. Not only this but it is cheap as well, we are able to acquire the material and have it fabricated to our exact design for under $600, by far cheaper than any other option.

Upon selecting 6061 Aluminum Alloy, stress tests were conducted for both climbing up and descending the pole by the mechanical team using computer programs. They discovered not only will aluminum 6061 suffice, but it performs quite well. Climbing up the pole, the maximum deformation, centered around the knee is expected to be 0.465mm, at a max shear stress of 20.78 MPa, and a max normal stress of 37.45 MPa.
The results for shear and normal strain were 0.0008 m/m and 0.0002 m /m respectively. Noting that the max strain occurs at the connection point between the footplate and gaff. While descending the pole, the max deformation is 0.2013 mm. With a max strain of 0.16346 m/m and
equivalent max stress of 7.317 GPa, with the normal max stress at 3.227 GPa. Making aluminum by far the most suitable option for purposes of our lower limb exoskeleton.

Motors

One of the primary components that will make the exoskeleton function is the motors. We did incorporate four motors, two at the hip and another two at each knee. We began our selection process by gathering information and testing different motor types. Prior to testing, it was important to understand the different types of motors available to us and their different advantages and disadvantages. It is critical to understand how these differences relate to our system requirements to make the best decision.

The two overall types of motor are AC and DC motors, named after how they are powered. The DC motor was a quick decision due to the clear advantages. DC motors provide a quick start-up and high starting torque. The nature of the exoskeleton requires short bursts of high torque which can be supplied by a DC motor. There are many types of DC motors to consider, again, with their own advantages and disadvantages. The types of DC motors that were most likely to fit our system requirements were brushless, brushed, servo, stepper, and hub motors. These types of motors required deeper research and then testing.

To get good insight on what motors are used in other common applications we began our research by looking at hobby and Do It Yourself (DIY) communities. Both of these communities provided a good outlook on what types of motors people are generally using for different applications. The good thing about these forms and blog posts is that they give accurate and true user experiences and installers testimonials.

It became apparent that a large number of these hobbyists used DC brushless motors, with a HALL sensor built in. This gave the user of their device full control over the motor when paired with an ESC (Electronic Speed Controller). This was a common factor among DIY drone builders, RC car enthusiasts, and motorized longboard builders.

It is important to still look into other motors as there could be a better option that we are overlooking. Servo and stepper motors were a logical pair of motors to research. As both are relatively similar with minute differences in performance and control.

The table below compares the first motors that we have considered when looking for a motor to attach to the joints of our exoskeleton.

Table 3.3.2: First Motor Comparison

Motor Comparison		
	Servo Motor	**Stepper Motor**
High torque rating	At High speed	At low speed
Pole count	Usually 4-12	Usually 50-100
Size	Longer body	Smaller size
System	Closed loop	Open loop
Price	>$300	>$60
Responsiveness	Delayed starting	Fast response
Locking mechanism	Electrical Servo-lock	Magnetic teeth

Servo Motor

Servo motors are a type of actuator that can create either a linear or rotational movement. Servo motors are generally used for precise motions and can make very small movements. They give strong control over the angular position of the motor which allows precise motions. These motors were considered because they have fast response rates and good control. They are also very commonly seen in robotics which would help with implementing them into this type of system. The difference to robotics is the introduction of being attached to a person. The error associated with relating human motion to the motor could cause damage to this type of motor. Additionally, we need a wide range of motion, which the servo motor does not provide.

Stepper motor

Stepper motors are similar to servo motors in the sense that they are known for their control over the angular position. Stepper motors are great for their reliability, toughness, and how simple it is. The maintenance is very low and offers a fast response to any direction needed. Fast response is important in the motor because there are sensors to measure human motion, and the motor needs to respond and move almost immediately to keep up with the person.

A downside to stepper motors is their low torque to inertia ratio. Its acceleration is also a lot slower. The motors respond quickly, but they might not be able to accelerate as quickly as the person using the exoskeleton. Stepper motors have an issue where their body can get very hot in peak performances. In the expected environment in which the exoskeleton will be used, overheating is a concern, and using a motor with these concerns would not work as well as other motors.

Brushed DC motor

A Brushed DC motor is the simplest of motors that receive power through a positive and negative wire. A brushed motor is the most simple in design and is used by all the motors due to there not needing to be a motor control board. A brushed DC motor only requires an input voltage and it will produce torque. That is due to the brushes being the only things needed to determine when the electromagnetic switches polarity. Apart from being the cheapest of the DC motors, the brushed dc motor is far more efficient than the brushless DC motor.

It takes far more electricity to produce the same amount of power. The reason is, there is friction generated within the motor due to the brush rubbing on the inside. This means a brushless DC motor can run for 50% longer than a brush. The biggest downside of using a Brushed DC Motor lies in the fact that the brush that supplies the power to the motor’s coils will eventually break and leave the motor useless.

Hub motor

A Hub motor is a special type of motor it is placed inside a wheel which allows it to drive directly. They are generally a specific type of DC brushless motor. They were mainly designed to be attached to bicycles but can, and have, been implemented into many other vehicles with wheels, especially electric skateboards. Hub motors are fairly cheaper than other types of motors. This is due to the very large increase in demand for hub motors and a supply that quickly matched. Commercial hub motors quickly became available everywhere with many applications. The biggest disadvantage to hub motors is the gears. Over time, the chain can cause a tooth to break off and eventually break the motor.

A hub motor would be an interesting way to actuate a joint while taking up very little space in an exoskeleton. However, our lower limb exoskeleton joints were designed prior to the electrical engineering team joining the project. Limiting our options to other motors.

The tables shown below compare the different types of electric motors in terms of longevity, complexity, price, and sound.

Table 3.3.3: Second Motor Comparison

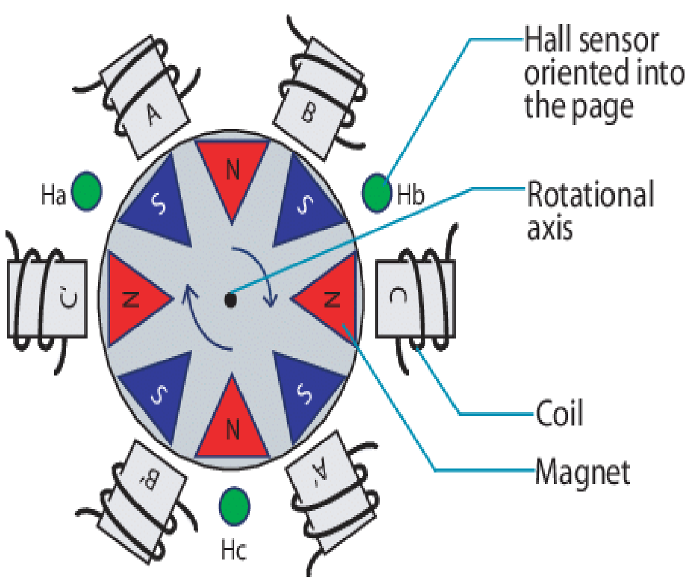
Second Motor Comparison			
	Brushed DC Motor	**Brushless DC Motor**	**Hub motor**
Longevity	1,000 to 3,000 hours	10,000 hours	3,000 to 10,000 hours
Complexity	Less complex it can be actuated by a DC voltage	More advanced as it needs a controller	Less complex as it's mainly a spinning magnet
Price	>$150	>$150	>$300
Sound	Noise due to friction against the commutator	Quieter due to no moving parts that can cause noise	Quieter due to no moving parts that can cause noise

Brushless DC Motor

Brushless DC motors are the most available motors that provide higher torque than DC motors and do not have the brush. The way they are able to remove the brushes is by using sets of stators that remain motionless. Stators are electromagnets created using wound copper wire that activate one after the other to pull a set of permanent magnets on the outside in the desired direction. Since the stators are on the inside and remain motionless relative to the input cables there is no piece, like the brush on a brushed DC motor, that will wear away thus the brushless DC motor has a much longer lifespan.

A downside to brushless motors is the back EMF that needs to be dealt with both mechanically and electronically. In order to use a brushless motor in our design we would need to gear it down considerably. In order to use a brushless motor, it needs to be connected to a motor control board. The motor is connected using three wires each connected to two electromagnets. The motor control board is where the software is stored that controls how the motor operates. A user has the ability to program the board to make it more conducive for a certain task. For example the software can control the RPM, the voltage applied, or the base current draw. The motor control board uses that information to determine the sequence it will provide voltage to the three wires going into the brushless DC motor. The motor control board will provide a stepped sine wave function input to each wire. The stepped sine wave functions are delayed so that once one is at its peak the sequential one begins.

Figure 3.3.1: Diagram of a Brushless DC Motor



There are two kinds of brushless DC motors. The first type is the inner rotor type. When the motor is an inner rotor type, the stators are located on the outside while the rotor is on the inside of the shaft. The permanent magnet is located around the rotor. Using this method there is less mass on the rotor and shaft therefore there is a lower moment of inertia. With that low moment of inertia, the motor can accelerate and decelerate quickly.

The other type of brushless DC motor is the outer rotor type. That type utilizes stators on the inside of the rotors. The permanent magnet is placed on the inside of the rotor. Due to the design placing more mass on the rotor, the moment of inertia is larger and therefore has less acceleration and deceleration. Though with the larger size there can be more magnetic poles. With the increase in magnetic poles, there can be a higher power-to-size ratio. Due to the stators being located on the inside, the heat radiation produced by the stators needs a way to ventilate and disperse. Usually, that problem is resolved by using ventilation holes in the rotor cup.

The tables below summarizes the differences between the different brushless DC motor accessories being considered and tested for the exoskeleton.

Table 3.3.4: Brushless DC Motor Accessory Comparison

Brushless DC Motor Accessory Comparison			
	Brushless DC Motor with only Software	**Brushless DC motor with Hall sensor**	**Brushless DC motor with optical encoder**
Positional accuracy	>75%-80%	>85%-90%	>90%
Price	>$15	>$35	>$35
Stall torque	Minimal	High	High

Brushless DC Motor with only Software

A crucial part of operating a brushless DC motor is being able to tell when to activate the next set of stators to pull the motor in the desired direction. There are multiple ways to communicate the positional information to the motor. The simplest is to just allow the motor control board and software to read the current draw and back EMF to tell where the motor approximately is and the motor will guess which way and begin activating the stators which will eventually cause the motor to move. The drawback of using this method is when the motor has initial stall torque, the motor will continue to change the stator that is on and cause the motor to not pull with the torque that it could. For uses that need to overcome that stall torque, the motor needs additional sensors to know where it is positionally.

Brushless DC motor with Hall sensor

One of the possible sensors that can be attached to the motors is the Hall effect sensor. A Hall effect sensor is a magnetic field sensor that works using the principle that when a wire with current going through it is acted upon by a magnetic field, it will produce positive or negative voltage depending on the side.

These sensors are either mounted to the stator or the rotor and are used to detect when a rotor has passed and if it has a positive or negative charge.

Although this does not give the exact position a motor has turned to, it does allow for the motor to know which stator is supposed to be powered and will continue to provide power to that stator to overcome the stall torque faster than if there was not a hall sensor. Another advantage is that the hall sensors are cheap and are built into some motors, so if there is only the need for approximate positional sensing the hall sensor is superior.

Brushless DC motor with optical encoder

Optical encoders are the larger more precise sensor that can be integrated into a brushless DC motor. An optical encoder consists of a circular disk connected to the rotating shaft of the motor. That circular disk has alternating areas of transparent and opaque around its circumference. Above the disk is a light source (usually a LED) that emits pulses of light.

Below the disk is an optical sensor that picks up the light as it pulses and goes through the transparent part of the disk. Using the signal of the optical sensor the optical encoder can detect the rotational speed of the motor. Since the motor software has precise knowledge of the speed the shaft is moving it can keep track of where the shaft is located in degrees. This method requires more space than a hall sensor but provides a significantly more accurate reading.

Not all optical encoders provide the same amount of accuracy. When an optical encoder has more slits in the disk, it is able to have a higher accuracy in the position of the motor. Newer optical encoders use electrical interpolation using a pseudo sine wave instead of a pulse signal.

Current Draw

The current draw is an important factor when deciding which motor is best for any choice of application. The load that a motor provides is what determines its current, hence the current draw. When a motor is spinning freely or has no load, the current draw is at its lowest. As there is more load placed on the motor, the current draw is increased until the motor is at its stall torque and will consume the maximum current. Understanding the current draw curve is crucial to know when working with mechanisms that will place a load on the motor and is a factor when determining your power source.

Stall Torque

Stall torque is the amount of torque that is produced when the output rotational speed is equal to zero. Stalling occurs when the amount of load torque surpasses the amount of torque generated by the motor shaft. This is important to know when determining how much torque a motor can produce before stalling. When a motor is stalling, the current draw is at its maximum.

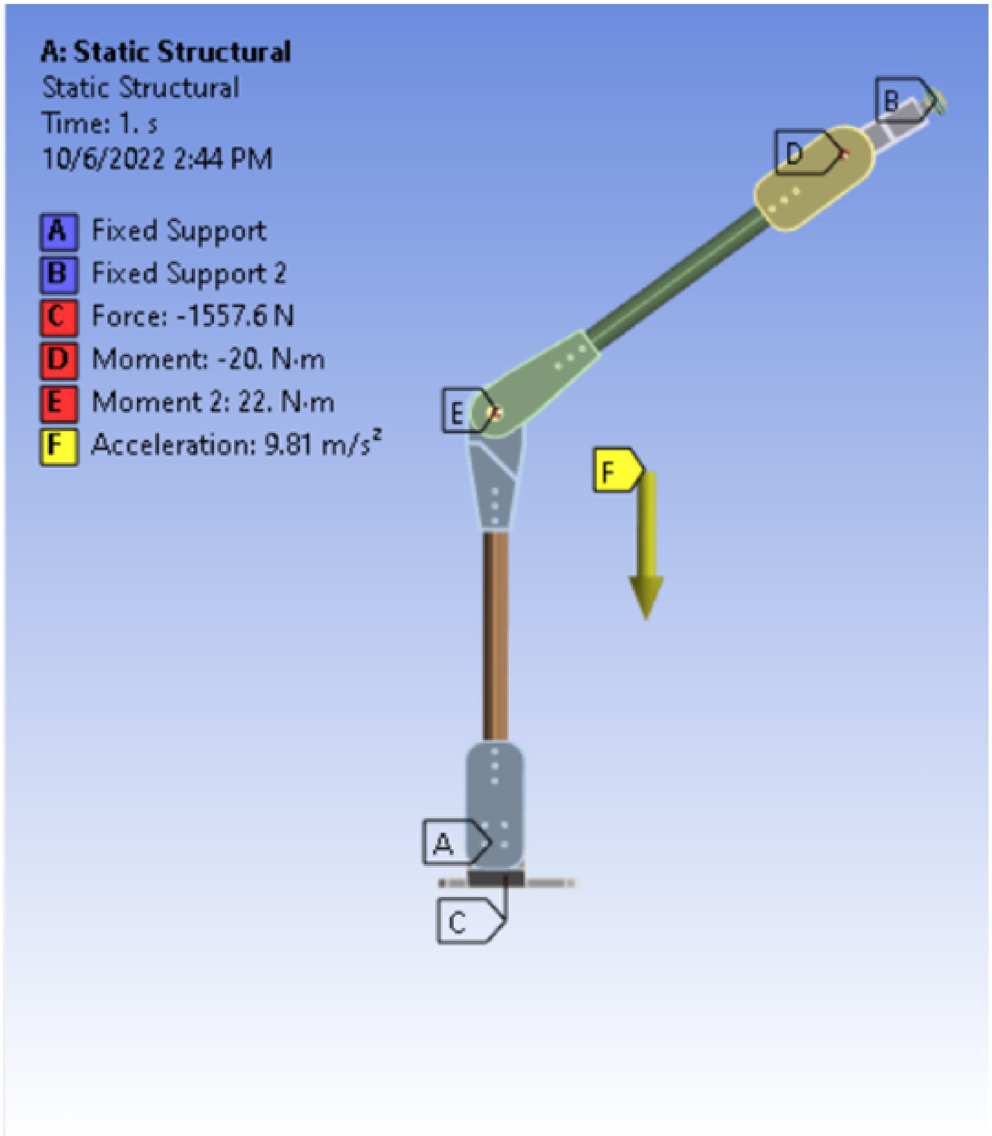
In terms of an electrical motor this also means that the shaft is motionless while the motor control board could not realize it has. If the motor does not have a hall sensor or an optical encoder the motor will attempt to rotate by switching the stators that are on but will not generate enough torque due to the correct stator not being consistently on. Another issue specific to electric motors is that when a motor is left in a stalled position, the motor can overheat and damage the internal circuitry and stators leaving the motor useless.

Stall torque is also a required measurement when dealing with robotics that will experience resistance forces that can cause the motor to stop. The stall torque needs to be high enough to overcome the stall to avoid overheating.

Required Torque

When selecting a motor we need to have an understanding of how much torque the motors need to produce. Using the dimensions for the frame created by the MAE team, we can calculate the amount of force needed to be produced in each joint. The force calculated is for one side of the exoskeleton, that being one hip joint and one knee joint. That is due to the climbing motion only applied force to one of the legs at a time. The model below provides an analysis of the forces in action during climbing

Figure 3.3.2: Static Structural of the Exoskeleton’s Leg



This model is an accurate representation for many reasons. First, the material properties for all the parts were set to be the same as aluminum 6061. The climbing of the pole is very similar to how someone would climb a stair step; therefore, the team researched the physics behind stair climbing to represent values in this study. The mesh used in the system is an accurate representation and has a finer mesh in the weak points of the exoskeleton. The study used is a static structural test with large deformation, which will allow for a nonlinear static study.

The first conditions to discuss are the fixed supports. There are two fixed supports used in this study: the first being at the connection between the gaff and the pole (**point A**) and the second being the connection point between the waist and the hip joint (**point B**).

The next set of conditions to discuss are the forces applied to the system. In this case, there is only one force applied and it is applied to the footplate at a magnitude of 1557.6 N (**point C**). This force represents the initial step onto the pole since this will be where the most force is needed to climb up.” Kresl, et al, page 25.

Gears/gearboxes

Gears/Gearboxes, also known as gear/speed reducers are a set of gears that are placed onto a motor. It allows the motor to reduce its speed and as a result, it would increase its torque. There are many types of gearboxes such as spur gear, helical gearbox, and bevel helical gearbox, each with its own advantages and disadvantages. Gearboxes are able to amplify torque by using different gear ratios. The higher the gear ratio, the more the torque is amplified. There are many considerations when implementing gearboxes into a system, especially when the application introduces a high amount of human error. If there is a high gear ratio, it is very difficult to turn the gears if the power supply or motor stopped working. There is also a risk of backlash when using gears. Backlash can cause damage to the gearbox or to the motor itself. This risk can be reduced by using special anti-backlash gears that use a spring to stop backlash regardless of direction.

Gears and belts will be a necessity in our design as we are very limited with the overall weight and shape of the lower limb exoskeleton. The weight has a direct impact on this because this will limit both the batteries and motors that we are able to purchase. Furthermore the shape of the exoskeleton limits both the battery and the motors we are able to include because we must not have an cumbersome or bulky design. These limits will result in motors and batteries that can not support levels of torque above 5 newton meters, per motor. However, with a gear and pulley system we are able to multiply our torque and increase our power output. Ideally a 2:1 or 4:1 gear ratio will help increase our torque above 25 newton meters.

One of the downsides of using a gearbox is that they have little to no repairability. When a gearbox malfunctions due to the gears wearing down, the only way to fix the machine is to replace the gearbox entirely. Gearboxes also require higher precision than that of a belt drive due to each gear needing to be placed exactly in line with the gear powering it.

The table below compares the various types of gearboxes that were being considered and researched for the project.

Table 3.3.5: Gearbox Comparison

Gearbox Comparison			
	Spur Gear Box	**Helical Gearbox**	**Bevel Helical Gearbox**
Design	Most simple	More advanced	Average
Power Capacity	Smaller applications	Preferred for high speed applications	Mixture for smaller or larger applications
Orientation	Parallel	Helix	90 degrees
Radial/Thrust Force During Use	N/A	N/A	Radial/thrust force
Vibration/Noise	Vibration increases with speed	Comparatively lower vibration and noise	Comparatively lower vibration and noise

SD2 Update a belt drive pulley was used for this instead as it was the most logical system to use that became apparent to us as we built the device.

Belt Drive

Another way to increase the torque ratio produced by a motor is by using a belt pulley system. Using a belt consists of having two different sized pulleys with one attached to the input torque and another connected to a part that the torque needs to act upon. Using a smaller pulley on the input and a larger pulley on the output creates a gear reduction ratio that will decrease the rpm and increase the torque. When using a larger pulley on the input torque and a smaller pulley on the output creates an increased gear ratio. That provides a higher rpm to the output but reduces the torque.

A belt system differs from a gear box due to it requiring more room to operate, but is less precise in machining. Having easier machining means it is easier to replace if anything goes wrong. Though there is a higher chance for mechanical failure due to the belt being made out of a pliable material. An important aspect to consider when using a belt drive is the belt's tension and slack.

When a belt drive is active the part of the belt that is being pulled by the input pulley will experience an amount of tension that needs to be considered when determining how tight to attach the belt. The same should be considered with the other side of the belt that will be experiencing slack from the output to the input pulley. If that side has too much slack it can lead to failure in the belt drive system. A belt drive can be either enclosed or open depending on the space requirements and user safety needs.

Enclosing the belt is required when the belt would be exposed to any user due to the fact that any material that gets caught in the belt would get pulled into a pulley and damaged. A belt can also be a danger if not enclosed if the belt breaks at any point during operation. The belt would become a projectile that could injure a user. For designs that are not near a user during operation, an open belt drive is more desirable due to lesser material cost and easier maintenance work. Another advantage when using a belt drive is that the input pulley and output pulley do not need to be completely aligned. There are belt drive systems that use up to a quarter turn in difference between the pulleys if necessary.

When designing a system with a belt drive the designer must consider which type of belt to use. The most common and simple type of belt is the flat belt. That belt consists of a rectangular cross section with many tension cords placed in a line to create the flat appearance with a top cover and bottom cover. The tension cords are made with steel or another high strength synthetic material. Usually the bottom cover of the flat belt is made with a high friction material to grip better on the belt drives pulleys.

An advantage to using the flat belt is that the belt can be used on both sides if the belts are arranged in a way that requires the use of both sides of the belt. Another type of belt is the v-belt. A v-belt consists of a trapezoidal cross section that fits in a deeper and thinner grove in a pulley. A v-belt has a larger volume, tensile strength, and surface area contact with the pulleys. V-belts are the most commonly used in industrial settings where the belt is needed to be considerably more durable than that of a flat pulley.

The table below compares the different types of belt drives considered for use in this project.

Table 3.3.6: Belt Drive Comparison

Belt Drive Comparison

	Flat Belt	**V-Belt**
Cost	Lower	Higher
Tensile Strength	Increased by making it wider/thicker	Increased by adding more v-belts
Durability	Easier to break/puncture	Harder to break/puncture
Bidirectional	Yes	No
Efficiency	>98%	>95%
Belt Lifespan	>7 years	>6 years
Best Used at High Speeds	No	Yes
Noise Emission During Use	Quite	Whistling noise
Tension During Installation	Calculated	Estimated
Large Power Transmission	No	Yes

Back EMF (Capacitors)

Back EMF is an electromagnetic field that is produced due to the flow of current through the coil of an electric motor. It is Lenz's law and acts in the opposite direction to the voltage. It is important to know because If there was no back EMF, the motor would be able to run. The speed of the motor is directly related to the back EMF. The back EMF causes a spike in the voltage when the motor decelerates or brakes. This can create an overvoltage flow to the power supply. Overflow voltage to the power supply will cause serious damage and could possibly destroy it. In order to avoid overvoltage, the back EMF energy needs to be captured before reaching the power supply. This can be accomplished using either diodes or capacitors. The motor control board will contain capacitors in order to prevent damage.

Another aspect of back EMF is the force that it will apply when the motor is not powered but is being moved by another force. In our case it is when the user is moving their legs. The amount of resistance force is low, but when the motor is geared down the resistance is amplified to the same degree as the motor's input torque. Though, for our exoskeleton, the only time the user is not going to be using power is on the descent. We can use the resistance force to our advantage to add a sort of suspension to the descent to reduce the impact of each step down the power pole.

Bearings

In order to have the joint and pulleys freely move rotationally while maintaining structural stability we did use bearings. A bearing is a mechanical component that reduces the friction between two rotating parts or linearly moving parts. In our exoskeleton we did use the bearings to move two rotating parts. They are commonly used to hold rotating components such as axles and shafts. They function by having two circular metal pieces with a groove on the outside of the smaller one and a groove on the inside of the large one. The metal circles are placed inside of each other and the space between them is filled with metal balls. That mechanism allows the outer circle to spin freely from the inner circle and vice versa without compromising the structural integrity of the two pieces.

Standoffs

For the pulley system to work we require the use of standoffs. A standoff is usually a cylindrical metal tube with threading on both ends. For our exoskeleton project we did utilize those standoffs to add a space underneath the motor for the pulley and belt drive to operate. Standoffs can be made at a larger diameter to increase the stability but reduce the space it creates. They are also made of many different materials but are most commonly made of aluminum.

Standoffs can be found in either round or hex shapes depending on the need of the component. Standoffs can range in size from microns to inches. The smaller standoffs are used in circuit boards to separate layers of a PCB in a uniform fashion. The larger standoffs are more robust and are used to space larger components from each other. A standoff can have a knurling on the outside of the surface to give the standoff a firmer grip.

Sensors

Sensors will be a big part of our control system. It is important to select a sensor that is going to accurately control our motors and enable assisted movement whenever it is necessary.

Accelerometers

Accelerometers are prominent today. Almost any data around movement includes an accelerometer that outputs a signal based on either X, Y, or Z positioning. Knowing XYZ coordinates is powerful for inquiring about information. With the use of these three inputs, an accelerometer can measure numerous things. One major data type included in the name is the ability to measure acceleration. Numerous technologies use accelerometers, such as smartphones and drones. Accelerometers can even be found in the biomedical field to count steps and activity monitor movement, which can directly be correlated to the exoskeleton movement.

The choice of an accelerometer is not only because of its wide off-the-shelf availability but because of how programmable and diverse they can be used for regarding the demands of the sponsor. The team's accelerometer needs to be able to perform unique tasks, but nothing that has not been experimented with before. Having previous tests and data is vastly beneficial in understanding the capabilities and limits of any technology, and the more accelerometers have been in the field assists with the team's own calibration and testing. It's key to note early on that accelerometers cannot record movements such as cycling, yoga, or sitting activities.

The objective of an accelerometer in the team's project revolves around detecting steps and having immediate feedback to understand physical activity and inactivity. The team has decided to distinguish the possibility of using a pedometer, which from a preliminary standpoint, is very similar. The purpose of knocking a pedometer out of the running for technologies used in this project is the lack of possibilities for recording known errors through other experiments.

The main choice was found when a study showed that a pedometer would detect movement outside of the wearer (body) and not be able to differentiate this from the user. Accelerometers, with proper coding, have the capability to distinguish these movements, and this is critical to our objective.

This ensures accurate data and can ultimately be a safety hazard if incorrect data from different sources occurs. Moving onto what an accelerometer consists of, it is important to understand all components internally. Accelerometers have capacitive plates inside their casing. These can either be fixed in place or attached to tiny springs that react to movement, such as acceleration. The movement changes the spacing between the plates, and this is internally outputted as an electrical signal to determine how the movement has changed.

Another construction of the accelerometer can be centered around piezoelectric components. A piezoelectric material can output a charge when it experiences mechanical forces. Once this force is felt, an electrical signal is sent based on how much force was applied. Breaking down an accelerometer into communication interfaces is also important for the electrical design of the project. There are three different key interfaces to bring up for the teams' purposes. These are the analog interface, digital interface, and pulse-width modulation interface.

All of these have the capability of communicating with the team's microcontroller, so breaking down the ability of each is necessary. With the analog interface, the accelerometer sends voltage signals at different levels to show accelerations.

This voltage signal can be sent to an analog-to-digital converter (ADC), which outputs the value that a microcontroller can read. These are the cheapest options out of the three.

The following communication interface is the digital interface. This outputs information through different protocols. Ideally, these are common such as SPI or I2C. The benefit of this direction is less room for errors involving noise. The last interface is the pulse-width modulation (PWM) interface.

The PWM outputs square waves at a given period. However, the duty cycle changes when acceleration changes and the output is found. The biggest benefit to all these interfaces is that no matter what the team decides, all accelerometers use hardly any power. This is ideal for our application, where the device might not get charged for multiple hours. Accelerometers, on average, work off 5V or less with only a couple of milliamps. The unique ability of coding can also allow the user to have different modes of the accelerometer to save power when needed.

Some additional features of accelerometers are useful to note. These range from free fall detection to tap detection for situations where the accelerometer needs to change modes or be turned off. Other add-ons can be applied, which will enhance the accelerometer capabilities. Internal measurement units (IMUs) can be used to add gyroscopes or magnetometers for motion tracking or guidance systems.

This is all done through the range of which an accelerometer reads, ±1g up to ±250g. Accelerometers are off-the-shelf, typically small and have complete 3-axis capabilities. These can be 4mm x 4mm x 1.45mm and function as low as 1.8 volts at 0.35 milliamps. Bandwidths can be changed to suit the user application in real-time, and these can range from 0.5Hz to 1600Hz at an X-Y range, while the Z range functions from 0.5 Hz to 550 Hz.

The specific accelerometer being researched also contains signal conditioning circuitry which utilizes open-loop acceleration. This will be instrumented in our design, as well as the use of the analog communication interface. To overcome any issue of electrical noise, a 0.1 microfarad capacitor will be placed at the supply voltage pins. Alongside this will be a 100-ohm resistor in line with the supply line. What this creates is a typical RC filter.

Hall Effect Sensor

The hall effect sensor is a very useful sensor for understanding magnetic flow and converting these forces to a readable and usable value. The output of this sensor directly correlates to the strength of magnetic force. With the ability to activate from an external magnetic field the user can gain flux density and polarity characteristics. As these characteristics are detected and the calibrated threshold is met then the hall effect sensor generates an output voltage to send as an analog signal. This voltage is known as a Hall Voltage. The internals of these devices show how and why they work.

There is a thin rectangular semiconductor (p-type) inside of the casing. This semiconductor is typically a material like indium antimonide or gallium arsenide which are excellent metals for passing current. As these materials are placed near a magnetic field there is invisible flux that acts upon the semiconductor. This force deflects charge carriers and separates them to each side of the material. This movement of particles is caused strictly by the magnetic force. This movement creates a potential difference from one side of the semiconductor to the other.

The magnetic flux, when perpendicular, allows the flow of current, typically in the south pole. The poles are key notes when discussing hall effect sensors. Majority of these are created to be normally closed (NC) which is an open circuit and does not allow current to be passed through. When a magnetic field is present then the user gets a closed circuit given the right amount of magnetic strength and polarity. The voltage output has a direct correlation to the strength of the magnetic field (output $\propto$ H).

Because the majority of these signals are too small for the average Arduino or voltage input module the use of a DC amplifier is typically used. The equation behind the hall sensor voltage is the quotient of the current and thickness, where VH is the hall voltage (represented in volts), the RH is Hall Effect coefficient, the I represent current flow through the sensor (represented in amps), the t is thickness of the sensor (represented in millimeters) and the B is the magnetic flux density represented in Teslas. Moving onto digital output there are two directions to go when dealing with a hall effect sensor. There are Bipolar and Unipolar types which work differently.

A bipolar sensor uses the south pole to function (closed circuit) and a north pole as the normally open (open circuit). This means that the south pole needs a positive magnetic field, and the north pole experiences a negative field. Unipolar, as the name might suggest, only needs one pole to operate. This uses the south pole to both open and close the circuit as the magnetic field moves to or away from the sensor. Now that the background and how hall effect sensors work is finished there are numerous applications that suit the teams' desires or interests. First it's crucial to understand all the different types of magnetic applications like Head-On, Push-push, sideways, etc. Each of these applications require a different set up and may result in what hall effect sensor the team uses.

For example, the head-on approach creates a voltage output signal in a linear configuration depending on how close or far the magnet is to the sensor. Sideways movements are wonderful for understanding rotational magnets for rotational speed of motors. This is because there is a fixed distance (air gap) between the sensor and the magnet. As the magnet passes through the zero-field center line the linear output is generated which can now be both positive and negative. This means the user can understand movements as vertical or horizontal.

Foot Pressure Sensor

Looking into foot pressure sensors can be a challenge at first because of the wide variety of pressure sensor applications. Diving into the team's purposes, a weight sensor (weight transducer) is the direction the team will dive into for our specific design. Weight transducers have the capability to turn mechanical forces into an electrical signal which connects to a microcontroller or processor.

The design from these sensors is far more simple than other sensors discussed. As the weight increases so does the voltage output. Key understandings for these sensors are getting the right calibration and making sure to stay within the component’s specifications from the data sheet (as is critical for any designed component). Getting into the weight transducer and how it works requires some mechanical understanding of strain.

For example, strain gauge (metal foil) is a specific sensor that changes its electrical resistance based on the force applied. This allows not only weight to be converted but compression, torque, tension etc. These strain gauges consist of electrical conductors that are in a tight zig zag shape. When the material is pulled (squished) the metal conductors stretch and get longer. Because the change in shape the resistance gets changed which as well directly affects the voltage output. The body needs to be strong enough to withstand large amounts of forces but elastic enough to deform and reform when weights are applied.

Luckily the team will be purchasing an off the shelf model and not have to calibrate these which requires more time and money than allocated. The body itself acts as a spring which assists in the deformation of the strain gauge. The use of a Wheatstone bridge circuit allows for differential voltage to be changed alongside the change in shape of the internal conductors. Now as the voltage is outputted an amplifier (strain gauge bridge amplifier) is needed to allow regulated voltage. This in turns converts mv/V output signal to something the user can record. The weight transducer can be correlated to a foot mapping sensor system.

A foot mapping sensor system allows for deep diagnostics on weight placement of the sole of a shoe. The mapping of this is used real-time to maximize human/machine performance. The data collection of pressure on a foot in different types of movements reveals lack of symmetry, overcompensation etc. Though these adjustments to weight load are minor it's been proven to provide a 0.25 second speed increase to professional sprinters, leading to the understanding that this is a crucial part of the design. Examples of these sensors already exist and have wonderful data to sample from XSENSORs Walkway and Stance Pads have been used with amazing results. These are made to gather high-quality balance, pressure distribution, and stance data for tracking the users' movements.

The table below is the comparison between the two types of batteries we are considering for the exoskeleton.

Table 3.3.6: Sensor Comparison

Sensor Comparison					
	Accelerometers	**Hall Effect**	**sEMG**	**Load**	**Pressure**
Price	~$20	~$10	>$20	~$15	~$10-$30
LifeSpan	3 years	5 years	-	10 years	5-15 years
Weight	1 gram	.1 gram	7.5 grams	.1 grams	.1 gram
Power Consumption	3 - 6 V	5 V	5.5 V	5.7 V	10 V

sEMG

Some exoskeletons in the market utilize EMG to receive input from the user. EMG stands for electromyography sensor. It is used to measure the electrical signals produced by muscles when they are activated. The most applicable type of EMG is the sEMG which uses surface electrodes to detect the electrical signal in your muscles. It is non-invasive and can be placed and removed with somewhat ease. The sEMG works best when placed at the innervation zone of both tendons of the muscle.

When the muscle is flexed, the sEMG sensor picks up the electrical signal and displays it on an oscilloscope. sEMGs are hard to incorporate into electrical designs due to the sEMG being very susceptible to electromagnetic interference. The sEMG sensor will measure voltage with very small amplitudes, usually around 30 mV when activated and 1 mV when not activated. Though, if the sEMG sensor is away from any potential electromagnetic interference and receives the proper voltage amplifying, it will be able to tell exactly when the muscle begins to move before any other sensor.

EMG sensors have been used in many medical robotics. The most prevalent form is prosthetic hands for amputees. These robotics hands utilize a system that is fairly similar to that of which we are trying to accomplish in our exoskeleton. The robotic prosthetics consist of a EMG band that monitors for muscle impulses in the remaining muscles of an amputee. Those sensors feed into a microcontroller that processes the data in the EMG sensors to operate motors in the robotic hand to allow the user to extend and collapse the hand.

Load sensor

Another option for a sensor that can take the input of the user's body is a load sensor. A load sensor is an electronic device that converts compression and tension forces into electrical signals. Most uses of load sensors involve telling the weight of an object using compression but can also be used to tell the tension of a mechanical system such as a pulley system.

In order to produce the desired signal from the load sensor, the sensor measures resistance inside the sensor. Two types of load sensors are the pneumatic and the hydraulic load sensors. The pneumatic load sensor uses a layer of gas in the load cell that provides an electrical signal when expanded or contracted that is proportional to the force applied to the load sensor.

Those types of load sensors are common in liquid or gas gauges to tell how much pressure is going through said gauge. The most common type of load sensor is the strain gauge load sensor. The design inside a strain gauge load sensor is a flexible diaphragm and wire. The wire is laid out in a grid pattern that produces electrical charge when force is applied. Those strain gauges are usually placed in a wheatstone bridge circuit.

A wheatstone bridge circuit consists of a constant voltage flowing through four resistors. Those resistors are laid out in a square shape with the constant voltage going into two opposing corners. If each resistor, or in this case each load cell, is equal the voltage between the other corners of the square will be zero. Using that principle, the strain gauges can be used to create an electrical signal that can be imputed into a control system of any sorts.

Control Boards

The control board will be the central component of the entire control system. The control board will be responsible for sending the right signal to the right place. It will take inputs from the sensors and send signals to the motors to turn on and off in order to enable proper movement.

Arduino

A microcontroller is essentially a computer that is embedded on a tiny circuit board and serves the function of computing and processing several tasks and computations. Furthermore, the microcontroller is also capable of delivering and receiving signals by use of different types of sensor pins: digital, analog, and protocol, to receive specific data from the environment that will then be sent to the electronic device it is connected to in order to relay the data. A microcontroller can output many different types of signals, such as light, movement, and sounds for electronic components, such as LED lights and motors. For a microcontroller to operate, it requires several other components: a power supply, an external source for software, and a stable clock signal. The microcontroller needs to be composed of a collection of all these components because, without all these external parts, the microcontroller would not function properly.

Arduino is a publicly accessible development board that was developed for creating programmable interactive designs using simplistic software and hardware for engineers and designers. Arduino can be used on a multitude of electronic devices that are capable of interpreting different types of inputs from the convenience of a computer. The platform is composed of a physically exposed programmable circuit board, usually described as a microcontroller. Additionally, Arduino software is a free integrated development environment, IDE, for the purpose of developing software that is coded in the Arduino programming language which utilizes the C and C++ libraries.

This can be accomplished by utilizing Arduino programming language, reference of the Wiring, as well as Arduino IDE, by reference of processing. Electronic components connected to Arduino can be powered by two different methods. The first option to power the electronic parts is by using the power from the computer that is connected to the Arduino board via a USB port. The alternative would be to use an AC adapter power supply that is ideally rated at nine volts. If both methods of powering the Arduino board are utilized then the Arduino will first consume power from the power socket port, before taking power from the USB port.

Also, having power connected from both methods is safe and will not cause any damage to the board. The pins on the Arduino board have an insignificant current rating and are only capable of powering electronic devices that require a small amount of current. In the case of using the Arduino board to power an electronic device that requires a high amount of power could result in perpetually damaging the microcontroller on the Arduino board. The recommended maximum amount of current that should be flowing through any of the sensor pins is 20 milliamps.

There are a variety of methods that can be used to control electronic devices that require a large amount of current. The use of a MOSFET can be incorporated by connecting to a digital pin on the Arduino board.

The programming language that Arduino is based on is derived from the open-source platform known as Wiring, in which similar elements are apparent in terms of the processing programming environment that is used. a resemblance of the hardware platform used for computing. Wiring permits the capability of coding cross-platform software to control electronic devices that are connected to a variety of microcontrollers, such as Arduino. The intuitive and simple nature of Arduino enables users of all kinds of backgrounds with different applications to use for creating prototypes, professional manufacturing, and educational purposes.

The development environment for Arduino is established from Processing which is also open-source and is a programming environment that is intended for making visuals and interactions. The Arduino board has many digital and analog pins on it that are used for transmitting and receiving the input and output signals. Arduino boards are limited to running one program at a time, unlike other competing boards, such as the Raspberry Pi that allows for multitasking. Like multi-core processors that can run more than one package without slowing down the whole gadget, the Arduino lacks this ability, and we would have to access one comic to run another.

The microcontrollers used in most Arduino boards are not equipped to provide full overall performance. The Arduino development environment is optimized for beginners with ease of sketching in mind. All this optimization is based on the reduction value of the usual power capacity of the microcontroller. If the same microcontroller is used with an AVR enhancement, the overall performance is accelerated through splitters.

Arduino forums are limited to Bluetooth phrases and help Arduino boards like the UNO don't have a built-in communication guide; we need to connect external hardware modules to activate these functions. Arduino supplies several boards with this technology, but the regular price is higher compared to the various boards available in the market. The external electronic components can also be controlled by the computer in the sense of controlling what the device does. The external power source for the Arduino needs to supply between 9 and 12 volts of power.

The Arduino UNO R3 board is one of the most common Arduino boards that is used today because of the simplistic, yet robust design. This particular board features a reset button, USB-B port, power port, and an ICSP header. The board contains a strip of pins that contains: 14 digital input and output pins, 6 analog input pins, and 6 analog output pins. The digital pin connectors are capable of only reading one out of the two possible values, this also applies to the output connector pins. The analog input connectors are intended for receiving voltage values that are transmitted by analog sensors and can read 1024 different voltage values. Also, the 6 analog output pin connectors are really digital pin connectors known as PWM pins that are used for receiving analog outs by means of digital inputs.

The board is composed of two processors: the ATMega328P is the main processor that is used for running the code and ATMega16U2 is the USB-serial processor that is used for receiving and delivering the data that is being transmitted. The ATMega328P memory utilizes a AVR CPU, reaching a performance level of 16 MHz, 32 KB of flash, 2 KB of SRAM, and 1KB of EEPROM. The ATMega16U2 memory is capable of storing 16 KB ISP flash, 512 B of SRAM, 512 B of EEPROM, and an on-chip interface used for debugging and coding.

A benefit to the ATMega328P processor is that due to it not being soldered directly to the board it can simply be removed and replaced in case it becomes damaged. The power required for this board to operate is between the range of 2.7 to 5.5 volts. The current flow rating for the pin connectors is 20 milliamperes. The security measures included on the board is a power on reset circuit that functions to generate resetting signals in the situation where the power is being fed to an external electronic device, thus ensuring that the microcontroller is being started at an established state. Furthermore, a brown out detection is another security that serves to detect any drop in the voltage supply that is below the rated voltage of the microcontroller. The recommended operating temperature range of the entirety of the board is from -40 degrees Fahrenheit to 185 degrees Fahrenheit. In severe temperatures the crystal oscillator, EEPROM, and voltage regulator could potentially malfunction.

The Arduino Mega 2560 is a much more robust development board that can be used for constructing more complex projects. The main processor of the board, ATMega2560, has a clock speed of up to 16 MHz, 256 kilobytes of flash memory, 8 KB of SRAM, and 4 KB of EEPROM. The USB-serial processor, ATMega16U2, is the same as that of the Arduino UNO R3. This board includes a variety of sleep modes: ADC noise reduction, power-save, extended standby, power-down, and idle. The board also includes two different ports for the power: USB port and an external AC to DC adapter port. The external power supply is rated at 6 to 20 volts, while the USB connector is rated at 5 volts.

Regardless of the maximum rating of 20 volts the recommended rating not to exceed is 12 volts because of the potential for the voltage regulator overheating and ultimately damaging the development board. Similarly, the minimum voltage limit is also not advised because the pins rated at 5 volts could possibly supply inadequate voltage and can cause the board to become unbalanced, thus why 7 volts Is the recommended minimum. The board contains 54 digital input and output pins, amongst them 15 of the pins are PWM pins, also there are 16 analog input pins. Additionally, the pins are rated at a voltage of either 3.3 volts or 5 volts. The DC current rating for each input and output pin connector is 20 milliamps. Conversely, the current rating for the 3.3-volt pins have a current rating of 40 milliamps and this value should be exceeded to avoid damage from occurring. The recommended operating temperature for this board is -40 degrees Fahrenheit to 185 degrees Fahrenheit.

RaspberryPi

A Raspberry Pi is a small-scale single board computer that is able to perform a variety of tasks similar to a regular computer. The circuit board of the Raspberry Pi is comprised of several components: system on chip, DSI display port, GPIO, HDMI port, audio jack, SD card slot, USB Type-C power port, status LEDs, CSI camera port, and RCA video outputs. The benefit of using a Raspberry Pi is that it is very adorable and accessible.

Furthermore, this board can support and be linked to many different types of sensors at the same time, thus allowing embedded system users to utilize the board for extensive applications. The board can support many kinds of programming languages, such as C and Python. Raspberry Pi's processor is faster than other microcontroller modules and Arduino.

The Raspberry Pi is essentially a microprocessor with an exceptional performing CPU, while the Arduino is only a microcontroller. The response time of the Raspberry Pi is higher than that of alternate competitor modules. If a monitor or display is attached to the Raspberry Pi, it can be converted into a small computer that can be carried around.

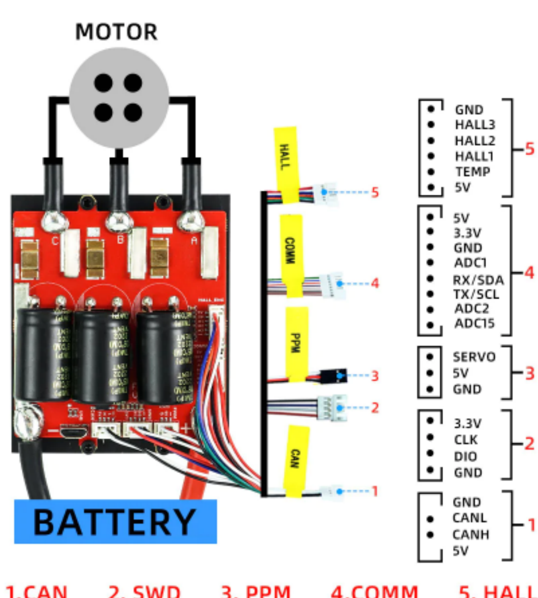
There are some disadvantages to using the Raspberry Pi: the main one is that it does not have internal memory storage such as an eMMC and the microSD is used as the onboard storage device. The launch speed of the Raspberry Pi is higher due to the microSD having a slow write and read performance capability as opposed to the embedded multimedia card.

The Raspberry Pi also does not have any method of cooling the board down such as a fan or heatsink, which in turn will promote overheating to occur and potentially cause permanent damage. The board heats up quickly when loaded with a powerful processor and other features. This is due to its smaller size and lack of heat dissipation units. Windows is the most popular operating system and is easy to use, but unfortunately, it is not possible for this operating system to be installed on the Raspberry Pi.

The Raspberry Pi 3 B+ board can be powered in two ways; first using the USB Type-C port and the second option would be to use an extra hardware attached on top component, Power over Ethernet, to obtain power from a network connection. The power supply needed is 5 volts rated at 2.5 amps and the required power to operate the microcomputer is between the range of 400 milliamps to 1.2 amperes.

Also, the power supply will turn on the Raspberry Pi the moment it is connected because there is no power switch or button located on the board due to keeping price at a minimum. The system on chip used on the Raspberry Pi 3 B+ is a Broadcom BCM2837B0 and contains a four core 64-bit ARMv8-A processor, 1.4 GHz quad core ARM Cortex-A53 central processing unit, Broadcom VideoCore IV 1080p graphics processing unit, and features a 1 gigabyte of RAM. Also, the specific Raspberry Pi mentioned features 8702.11n Wi-Fi and 4.1 Bluetooth capability. This single board computer has 40 general purpose input and output pins that can be utilized for a variety of functions. The on-board memory storage used is a MicroSD.

Electronic Speed Controller



Electronic Speed Controllers (ESC's) are a component commonly found throughout the remote control car, robot, and powered skateboard hobby communities. These have a wide range of applications, but they all share one thing in common, they are controlling electric motors. ESC's are specifically designed to control the speed, direction, and overall action of an electric motor.

Figure 3.3.7: Electronic Speed Controller

A signal from the ESC will raise and lower the voltage to the motor based on a given input. This will toggle on/off the motor as well as change the speed as needed. ESC's are designed with the "do it yourself" end user in mind. This being said, they are easy to program, and provide ample instruction in the form of a user manual.

For use in our exoskeleton, the ESC is an ideal component, featuring its own firmware, as well as multiple ways to program it. Furthermore, ESCs are designed to be operated in a similar system with comparable voltage and current ratings as to what we are expecting. They come in multiple power modes; DC, BLDC, and FOC(sinusoidal), getting powered via an 8 AWG positive and negative power cable.

As for control interfaces ESCs may have USB, CAN, and UART interface ports. Which supports PPM, ADC, NRF, UART, SPI, and IIC input sets. Additionally, the ESC can support sensors such as ABI, HALL, AS5047, and AS5048A. This is incredibly useful as we did use HALL sensors and others for user inputs. The 23 pins found on the right of the board allow for multiple inputs and outputs such as: HALL 1-3, TEMP, +/-5V, +/-3.3V, RX and TX SDA and SCL, ADCT, CLK, DID, SERVO, GND, and CANL/CANH. Pictured on the right is an ESC diagram featuring all of its components, as well as a guide to its pin layout. This shows multiple bits for various control inputs as well as control outputs to the motor. It pictures a positive and negative DC input and a three way power output to the motor in case you want to put it in sinusoidal mode. The 23 pins allow for many different software functions and ample programming opportunities.

Using the ESC in our system is the perfect application for such a device. Following the specs of our lower limb exoskeleton, this can handle a continuous current of 100A and instantaneous current of 200A, falling far below our expected currents. As for voltage the ESC can operate between 14 and 60 volts safe for 4-12S cells, however voltage spikes can not exceed 60 volts. Again, our expected voltage range falls well below this maximum voltage limit. The 10 AWG wiring from the board to the motor falls into spec for our lower limb exoskeleton, and lends itself well to being tucked away. One of the biggest benefits to the ESC is its size, being only 75.4x63.7x31.1mm, including the heatsink. This is easy to fit on our exoskeleton as it is not bulky and would be out of the way of the user. Additionally, the fact that the ESC comes with a heatsink and aluminum case enables us to protect the control board with its own built-in function. This mitigates risk and overall increases the reliability of our lower limb exoskeleton, as we are expecting the user to be bumping into objects and otherwise putting the exoskeleton in a harsh environment.

The figure below is a chart comparing all control boards that we were considering for the exoskeleton.

Figure 3.3.1 Control Board Comparison

Control Board Comparison		
	Arduino	**Raspberry PI**
Price of the control board	$60	~$120
LifeSpan	2,000 to 3,000 max charge cycles	300 to 500 charge cycle
Capacity	Loses actual charge capacitance over time	Retains charge better
Energy density of unit	High	Low
Weight of the control board	Heaviest	Lighter
How many pins are on the control board	85	40

GUI Interface

One aspect of the exoskeleton that is not required, but would add an additional level of user customizability and monitoring, is a Graphical User Interface or a GUI. The idea behind using a GUI for the exoskeleton is to provide a way for the user to input their weight to change how much force the motor applied at each joint.

For someone with a heavier weight, there would need to be more force applied at each joint. If the user is a lighter weight, too much force could be applied and cause balance issues and make the exoskeleton less easy to control. Another purpose for a GUI is to display the status of the batteries and program. This would allow the user to get a real time understanding of how much power is left in the batteries and get a software diagnosis if any component of the exoskeleton is malfunctioning.

The ways we could implement a GUI vary, but we narrowed it down to two methods with the first being attaching a LCD screen to the exoskeleton that can be turned on and viewed at any point without the need for an external device. The second method involves using an external laptop or smart device running an application that can connect to the microcontroller via USB to reduce the cost of the exoskeleton but will require additional hardware from the user.

LCD Screen

The first graphical interface we considered is the LCD Screen. The concept of using an LCD display is based on communicating hardware information to the user at any time. Information such as the battery level is the first one to come to mind, but with further testing we can determine whether more information is producible or needed.

The initial LCD display design considered and created was designed based on the only information being reported back to the user being the battery level. This is easily conveyed by understanding the power inputs to the components as well as the LCD display itself. The power supply current power containment loss can be seen in comparison to the total energy by function designs in the expected output of the initial design compared to the true, minimal loss, expectation. The initial important information from the benchtop and component testing is to fully understand the initial and final output associated with the design.

The types of LCD screens vary from TN (Twisted Nematic), VA (Vertical Alignment), and IPS (In-Plane Switching). A Twisted Nematic LCD screen is the most cost effective type of LCD screen. They use nematic liquid crystals inside two plates of glass. The nematic crystal, when power is applied to the electrodes connected to it, will twist 90 degrees. The TN LCD screens offer high response times and refresh rates but lack when it comes to viewing angles and backlight brightness.

Vertical Alignment LCD screens offer a wider viewing angle compared to the Twisted Nematic LCD. The VA LCD also has improved color and contrast but consumes more power than the TN. The last one is the In-Plane Switching LCD screen. That type of LCD screen offers the widest viewing angle out of them all with a high backlight brightness. The IPS LCD sufferers when it comes to refresh rate compared to both the TN and the VA LCD screens.

Laptop/Smart Device Application connected to a USB port

The device application functioning with real time hardware while connected through the USB port is essential to the component testing as well as the system testing being completed. No matter what microcontroller we utilize for the control system, we did need to have a way to view the status of the exoskeleton for testing. The decision comes in whether we did expect the user to have a laptop to access those status reports and to view the battery life. With the option of using a computer application to view the status we did not require additional hardware attached to the exoskeleton and did both decrease the cost and the power draw on the battery.

Battery

Extensive research must be done on the battery to ensure a suitable battery is found that meets our specs. There are multiple properties of a battery that must be considered for use in our lower limb exoskeleton. Most important is the battery's strength and capacity. The exoskeleton is intended to be used for at least an hour of continuous work.

Additionally, FPL is expecting the device to relieve the worker of about 20% of the force required to help them climb. This being said the motors must provide at least 25 newton meters of torque collectively. To achieve this with the motors we are researching the motor must receive somewhere around 10 amps and have a battery with a rating between 6 and 18S. This is anywhere between 22.2 and 66.6 volts at nominal voltage and 25.2 and 75.6 volts at peak voltage.

Aside from the required electrical specifications, a big factor of the battery is its dimensions as well as its weight. The battery itself must fit into a battery pack located on the back plate of the lower limb exoskeleton. This being said, the battery pack or battery for that matter must not exceed the dimensions of the backplate in length or width. Furthermore, the less the battery sticks out in depth, from the back plate, the better. We want to make sure the exoskeleton is ergonomic and out of the way of the user. Minimizing the size of the battery will ensure that the exoskeleton is less prone to accidental bumps and scrapes from the behind. The weight is also an important factor as batteries can get quite heavy very quickly. Keeping in mind that our exoskeleton shall not exceed 13.6 kilograms in weight it is imperative that the weight of the battery be minimized as to not make things too heavy, especially in the back end.

Lastly, but most importantly, safety. Safety is paramount and must be considered with every component that is added to the lower limb exoskeleton. The battery is one of the more at risk components in our exoskeleton. The reason being LiPo and LiPoly batteries are notorious for heating up when in use. This could be potentially harmful to the person operating the machinery if they were to directly touch the battery.

Furthermore, there is the inherent risk of an electric shock if the battery is installed poorly. Misuse of a LiPo or LiPoly battery can result in fire, explosions, or inhalation of toxic smoke. To eliminate these risks for the safety of our user, ample research will be conducted on which battery type to use, which exact specifications we need, and user testimonials to find a reliable battery. When installing the battery we did ensure all connections are secure and correct and that everything is compatible.

Lithium-ion

The lithium-ion (Li-Ion) battery is a rechargeable battery that has its cells contained in a hard-shelled housing that is composed of a lightweight metal, aluminum or stainless steel. Lithium-ion batteries are unique in the sense that they are highly energy dense which makes the battery efficient in terms of weight and size. Conversely, several issues can arise with the battery such as experiencing: high charging voltage, low charging voltage, or high current during discharging.

When the battery is overcharged or discharged thermal runaway will occur and ultimately cause the battery to explode or catch on fire. In regards to that issue safety measures are needed by integrating a battery management system, protection circuit module, or both safety mechanisms to the battery cell. These safety systems are designed to regulate or monitor the voltage and current to ensure the battery is within the rated limits.

The need for protection systems and hard-shelled housing also increases the manufacturing cost of the battery. Lithium-ion batteries also have a significantly lower self-discharge rate in comparison to other rechargeable batteries. Furthermore, another concern that arises is the battery's issue with aging. There are several causes of degradation that diminishes the capacity and power of the battery: irregular temperatures, current load, high/low cell voltage, mechanical stress, and life cycle. Lithium-ion batteries are also capable of being connected in parallel to increase the capacity of the battery.

The table below is the comparison between the two types of batteries we are considering for the exoskeleton.

Table 3.3.6: Battery Comparison

Battery Comparison		
	Lithium-ion (Li-Ion)	**Lithium Polymer (Li-Poly)**
Price	>$120	>$140
LifeSpan	2,000 to 3,000 charge cycles	300 to 500 charge cycles
Capacity	Loses actual charging capacitance over battery lifespan	Retains charge better
Energy density	High	Low
Weight	Heavier	Lighter
Charge cycle	Takes longer to charge	Relatively shorter charge time
Safety	Volatile at high temperatures	Generally safer, has a less chance of overheating or

Battery Comparison		
	Lithium-ion (Li-Ion)	**Lithium Polymer (Li-Poly)**
Price	>$120	>$140
		accidental explosion

Lithium-Polymer

A lithium-polymer (Li-Poly) battery is a rechargeable battery that has its cells contained in a soft-shelled housing composed of thin aluminum foil, thus making the overall weight of the battery very light; although is more susceptible to being damaged easier. The cells are able to be used in a multitude of electronics because of how robust the battery is in the sense that they are able to be produced in a wide variety of thicknesses, sizes, and shapes.

Lithium polymer batteries have a similar feature to lithium-ion batteries in that they can be connected in parallel to establish higher capacitance. Furthermore, the energy density of the battery in relation to the battery's weight is notably higher versus other battery types. The lithium polymer battery also requires safety measures, such as a protective electronic system or an embedded protection circuit to prevent the battery from being blown up when facing severe temperatures, overcharging, and exhaustion of the batteries capacity

Wiring Batteries in Series

When using multiple batteries, it is important to understand whether you are wiring them in series or parallel. When wiring a battery in series, the positive terminal is connected to the negative terminal of the next battery. By connecting the batteries in series you add the voltage produced by each battery. Although the voltage increases with each battery added, the amp hours remain the same. This type of wiring for batteries is useful when dealing with a device that requires high voltage and lowers current for a low amount of time. Batteries wired in series also can take more input power than those in series. An issue with using batteries in series is that every device in the circuit needs to either operate at a higher voltage or run through a voltage converter.

Wiring Batteries in Parallel

Unlike wiring batteries in Series, batteries wired in parallel do not increase the voltage provided. Batteries in parallel increase the amp hours additively by each battery connected in parallel. Running batteries in parallel is done by connecting each positive terminal to the other and each negative terminal to the other. An advantage to using batteries in parallel is that if one battery goes out, the system will still work at the desired voltage. A disadvantage to using batteries in parallel is that the lower voltage results in a higher current. Having a higher current causes the system to need larger wires to carry the power throughout the system.

Running two of the same battery in parallel will ultimately double the time in which we can run the exoskeleton for. Or, if time is not the issue, we can send more power to the motors, by increasing amps, and even increase the usetime. This could help increase the speed as well as the power output by the motors. Ultimately, putting batteries in parallel will suit our team the best with this lower limb exoskeleton because the batteries we choose should already have a high enough voltage.

Power Interface

Power Control Custom PCB

As a requirement of this project, the PCB designed for power distribution will be a necessity. This board will be responsible for the power flow to and from the battery. It will recognize and distribute power when the battery is being charged, and direct the power accurately when the device is in operation.

Charge Controller

When dealing with batteries it is important to understand how they will be charged and that they will be charged safely. Utilizing a charge controller is crucial in prolonging the life of a battery. Luckily Lithium Ion batteries can be charged a higher initial current than other batteries. The initial current it can be charged at is equivalent to the Amp hour rating of the battery.

Lithium Ion battery charging requires three components to ensure that they are constant. It must have an auto cut off at full charge, a constant voltage, and a constant current input supply. In order to tell when the auto cut off time would be you have to understand when the battery will be in its constant current state and when it will be in its constant voltage state. When a battery is depleted it will need to start with constant current to raise the voltage to its rated voltage.

Once it has reached that point the battery will be in its saturation charge state where the voltage remains at a constant value while the current consumption lowers towards zero. It is important to know when it approaches zero because once it reaches about 3% of the rated current the battery will need to have the input supply turned off.

Power Switch

A power switch is a crucial aspect of a control system to ensure the safety of the user. A power switch must be rated to handle the voltage that runs through the wire as well as have enough heat sink to cool the component to avoid any failure due to the component melting.

Another problem that can arise due to high voltages going through a power switch is sparking which is extremely undesirable when dealing with an exoskeleton that will be used at heights. In order to avoid any sparking you will need to ensure that the switch is well insulated and has the desired rating for the voltage going through the wire. Most switches work by simply opening the circuit mechanically when activating the switch.

Though there are newer switches that utilize the relays and electronic components instead of mechanical. Utilizing those types of switches are useful for multiple reasons. First they will usually indicate whether there is power going through the wire even while the switch is off. Electronic switches also reduce the chance of sparking since there are no opening connections to cause the sparking. An issue with those types of switches is that they produce heat where a mechanical switch would not.

COTS

The batteries can be controlled, charged, and discharged using a commercial off the shelf (COTS) power control board designed for the batteries being used. This would be ideal as commercially produced items are easier to source and can be mass produced as opposed to custom boards. This is especially helpful when considering we are designing this board for a customer, FPL. The company desires the capability to reproduce and replicate our design model in the future and eventually into full-scale production.

Thermal Cooling

When dealing with electronic components such as motors, batteries, and even microcontrollers it is important to understand where the heat is coming from and how to dissipate that heat. It is important to dissipate any produced heat to avoid melting any circuitry. Cooling electronic devices can be separated into two different categories. Those categories are passive cooling and active cooling.

Passive Cooling

The most cost and energy-friendly resolution to dissipating heat is passive cooling. Passive cooling involves using a thermally conductive material in direct contact with the surface of the desired electronic device. When the device produces heat, the thermal energy will be diluted into the larger thermally conductive material.

For devices that do not produce a lot of heat or produce most of their heat in a small area, passive cooling could be all that is required to prevent overheating. Heat sinks can be made with many materials, the most common being aluminum and copper. Aluminum is the cheapest material to create heat sinks with but has a lesser thermal conductivity than copper.

Copper and aluminum are used most of the time also due to how lightweight they are compared to other metals such as steel. Most heat sinks use a structure that utilizes a flat base with many fins extruding parallel to each other. Using that fin structure, it allows maximum air flow to move the thermal energy out of the system.

There are also pin structures that in theory have more surface area than the straight fin design, but when tested the straight fin was able to transfer the thermal energy faster and therefore was able to cool the electronics further. The most common use of heat sinks is with cooling processors and microprocessors due to the extreme heat production and potential for that heat to melt the interior electronic components.

In order to secure a heat sink onto the desired component, the most common method is to use thermally conductive tape. By applying that tape to the base of the heat sink, it ensures there are no air gaps that can prevent the flow of thermal energy.

Active Cooling

When passive cooling is not sufficient to disperse the thermal energy produced by a device, active cooling shall be used to deal with the thermal issue further. Active cooling is when the cooling process requires an external device to enhance the transference of heat. One of the most commonly used active cooling devices is the fan. A fan will move air throughout the electrical component and allow the thermal energy to transfer into the air. Although the air has a lower thermal conductivity than metal, when the air is moved at a high enough speed it disposes of the thermal energy faster than a passive cooling metal would. Active cooling is not only restricted to air.

Water cooling systems were invented as a way to use a medium with a higher thermal conductivity to move the thermal energy out of the electronic. By using a water pump, the water travels from a heat sink to a water basin. At the water basin, there may also be additional cooling units depending on the amount of heat created by the device. Active cooling is very useful to cool devices producing a lot of heat, but is quite a lot more expensive and requires themselves to have power. Most of the time, a cooling system uses both passive and active cooling methods to

Joint Cooling

The actuators located on the hip and knee joints of the exoskeleton need to function properly without fail, otherwise the motor will malfunction and ultimately render it to be dangerous for the worker operating the exoskeleton. The lineman workers climbing up and down the power poles produce heat, thus increasing the temperature of the motor.

Each motor has a specific temperature rating that indicates the max temperature that the motor is capable of properly operating at. Also, the environment that the lineman workers are in is typically hot and humid which will also play a factor in causing the motor to rise in temperature. The motor itself also produces heat that will continually raise the temperature throughout use. Another factor that will add heat is the friction between all moving components. The joint must have full range of motion which will always produce friction when implementing a motor, belts, and gears.

To ensure that the motors do not overheat and malfunction a cooling method needs to be implemented, such as using liquid to cool the motor and drop the overall temperature of the system. The liquid coolant system would be used to cool the fixed component located inside the motor, known as the stator. An additional safety cooling method can also be incorporated into the exoskeleton to provide additional cooling in case the motor's temperature rises abruptly. The use of a fan and radiator, or simply just a radiator can be installed at each of the joints near the motors to pump coolant and rapidly drop the temperature of the motors.

3.4 Part Selection

Component Testing

The electrical components that were researched and discussed needed to be tested. The research showed the motors that could be implemented into the system to be a DC brushless motor or a hub motor. In order to know which motor is better and the exact voltage, current, and torque ratings needed for the motor. After the motors were tested, we were able to know the requirements to choose the battery.

The motor testing first required preliminary testing with motors that were not going to be part of the official system or testing. Spare motors were used to reduce risk on any important components. The initial testing was done to properly understand how to connect a motor to a power supply and write the needed code to have the motor work properly. In the initial testing, we connected an Arduino microcontroller to a 5 V brushed DC motor and tested the torque using a string and a weight. Torque is a measurement of force on a distance, so this very basic test allows us to measure the actual torque output.

The same test was then run on a 5 V DC stepper motor. It was important to verify our expected results of using a stepper motor as well as understand a different type of motor in general. Each motor has its own signals and ways of being connected that vary slightly but are necessary distinctions to understand. This helped to gain an understanding of how to measure the stall torque as it relates to the current draw. The initial testing also allowed the team to understand the relation and ratio of electrical energy to mechanical energy. There is expected power loss when converting energy, but it is important to understand how much power loss is expected and how to measure it.

From the preliminary testing, we were able to begin designing a motor test bench that would mimic the knee joint of the exoskeleton while using cheaper materials and easier manufacturing methods. The purpose of the motor test bench is to test different motors, gear ratios, and motor controller settings. For the motor test bench, we used ¼ inch aluminum that could be drilled using a drill press.

Those aluminum plates would be attached using a metal rod and multiple bearings. The motor is connected to four spacers that allow the gears to lay underneath. The gears are 3D printed at varying sizes to test each parameter at the different gear ratios. Using the motor test joint, we were able to first attach it to a table using clamps and test the force it is able to apply from different angles. The joint was tested at 0, 30, 45, 60, and 90 degrees. Each angle was tested for its relative stall torque. The current draw was measured at each stall torque to quantify the expected maximum constant current flow.

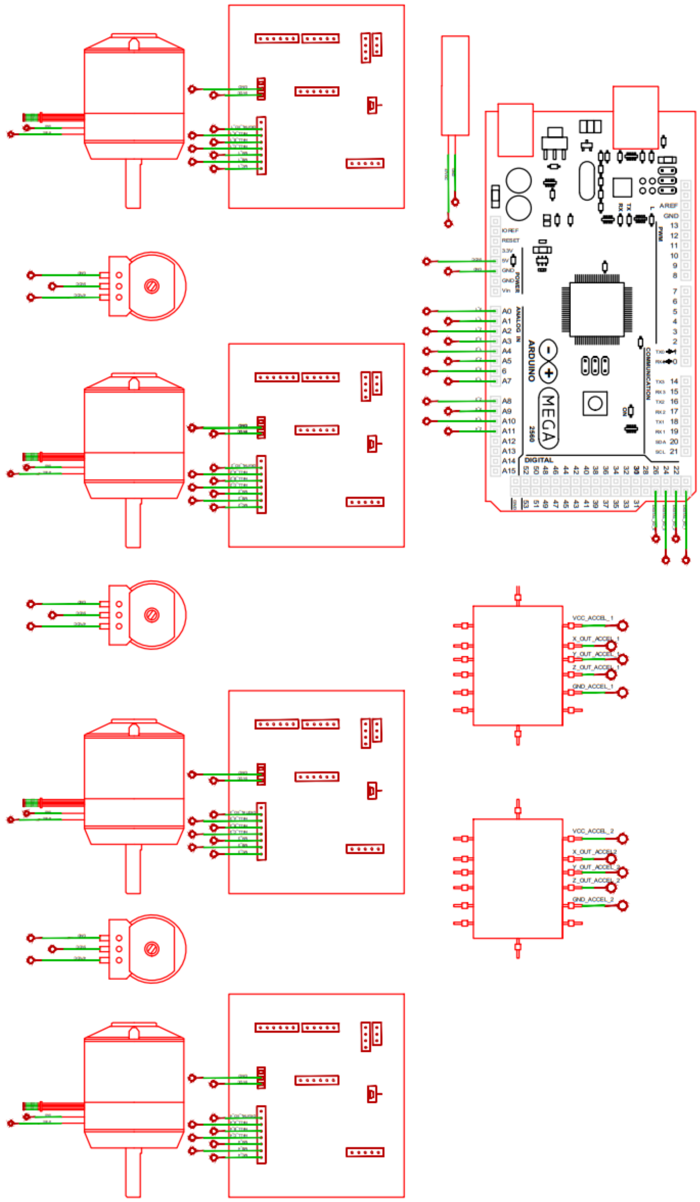
The next set of testing after the benchtop testing was to attach the motor test joint to a person's leg in the same way the exoskeleton will function. This testing gives the most realistic and accurate test possible compared to the expected general use of the exoskeleton. The benchtop attachment was unclamped from the table and attached to a team member's knee joint.

It was important to complete benchtop testing prior to this stage due to safety concerns. When testing has an increased level of danger associated with it, it is imperative to reduce risk and have an analysis of possible risks and how to mitigate them. This helps to keep everyone safe during testing. We have worked and tested to understand the torque value that could be provided by each motor, but it was necessary to understand how these torque values relate to the way they feel when used on a person’s joint. The purpose of the exoskeleton is to augment human motion of the hip and knee joints, so the tests needed to recreate that purpose.

The initial testing of the motors helped to verify the control system and motor connections as expected. This test also showed that a DC motor was the correct part and that DC brushless motors were a very viable option to implement in our system. The benchtop testing will later be recreated using the actual motor expected to be used with the system as determined from this testing.

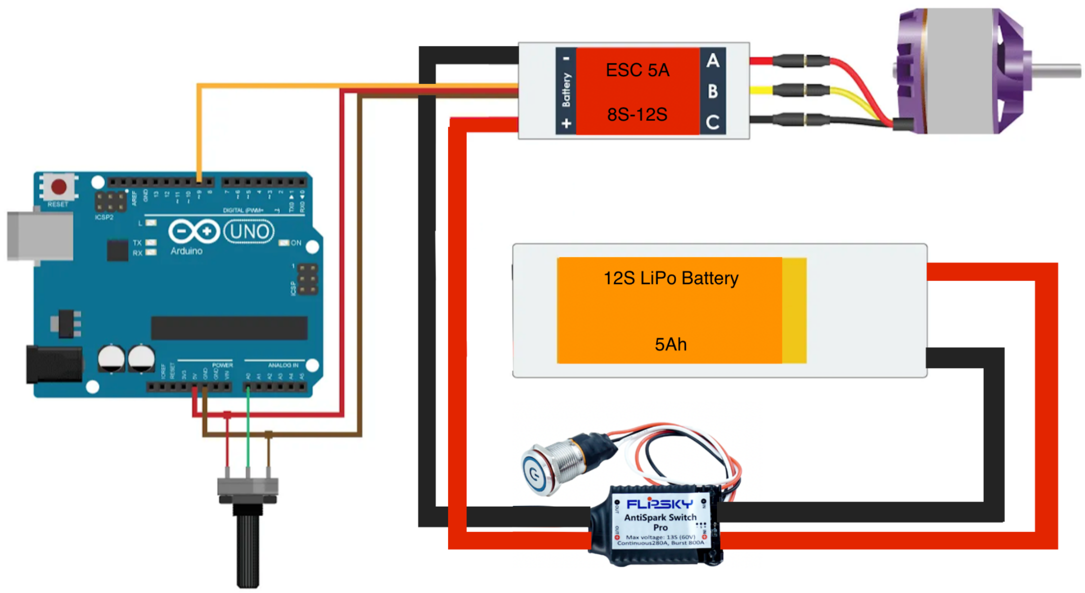
The figure below shows the connections that need to be made between the motor, control board, battery, switch, potentiometer, and Arduino that are necessary to complete testing. It also shows the electrical schematic for the exoskeleton system as a whole, including Arduino, motor control boards, batteries, motors, and sensors and their connections to each other.

Figure 3.4.1 System Electrical Diagram



The figure below shows the connections being made in the benchtop testing setup in order to test a single motor.

Figure 3.4.2 Testing Block Diagram



Frame

This project is sponsored by Florida Power and Light, there are two teams involved in the creation of this exoskeleton. The senior design two group and senior design one (This group.) The other team has been working on this project for a couple more months than us and has already created a 3D model of the frame that we did build. Our job was to select the best material and components needed for this build to be successful.

There have been numerous discussions on what material we would like the exoskeleton to be made out of such as aluminum and carbon fiber. Being on a budget and in a strict time frame, we needed to select a material that can be custom fabricated to match the 3D design and be made relatively quickly. In the end, we decided to choose aluminum for the frame. More specifically, aluminum round tube 6061. 6061 refers to the specific aluminum alloy that the metal is composed of. The metal can be purchased from practically any store that sells metal but for this project.

Motor

Our team is in the process of testing motors for different torques at a given voltage and amperes provided. The desired collective torque from all four motors at once is at least 25 Newton Meters. To achieve such a torque we must have a motor that can push 4 newton meters of torque, and have the capability of attaching to a pulley system. This way we can use a 2:1 or 4:1 ratio to get well over 25 newton meters of torque. We have narrowed down the type of motor to the brushless DC motor to be the motor of choice, however, we do not have a specific motor at this time.

Below is a table of our top three motor choices and their properties.

Table 3.4.1: Motor Selection

Motor Selection			
	Flipsky BLDC Belt Motor Battle Hardened 6374	**Electric Skateboard Motor BLDC 5065**	**137f Lifting Table Motor**
Rated Power	3250 W	1550 W	52.6 W
Rated Voltage	190 KV	190 KV	24 V
Max Power Output	2900 W	1550 W	-
Max Voltage	44.4 V	41.5 V	-
Current	85 A	80 A	14.7 A
Resistance	0.05 ohm	0.064 ohm	
Speed	170 RPM	6130 RPM	75 RPM
Torque	8 Nm	4 Nm	6.68 Nm
Poles	14	14	-
Weight	860 g	450 g	-
Width	63 mm	50 mm	59 mm
Length	101 mm	88 mm	156 mm
Price	$58	$80	$59.41

After a complex analysis of multiple different motors, both brushed and brushless, all for many different applications, we were able to compile a list of our top three motors. These motors can easily be sourced online from places such as amazon and aliexpress. It became apparent that the best type of motor was one used for applications that already have high power and torque requirements. For this reason, we looked into hobbies such as remote control cars and electric longboarding, and practical applications like motorized standing desks and garage door motors.

Longboard motors quickly became the preferred option because of their large amount of documented history and countless testimonials from satisfied hobbyists. This being said, they account for the first two out of three motors that made it to the final selection. These being the C6374 and D6374 brushless belt motors. Both of these motors had a high max power output around 3000 watts, reasonable max voltages, less than 80 volts, and a high enough max current around 100 amps.

Furthermore, both motors push about 4 newton meters of torque, with a proper pulley system, and four motors should give us the required 20 newton meters, if not more. Looking at the weight and dimensions the C6374 is 80 grams lighter and almost exactly the same size in width and length. It is important to note that these motors will have to be perpendicular to our frame, making the length more important as that is how far these motors will stick out.

Fig 3.4.2 137f Motor

Motors for more practical or industrial uses, had more interesting shapes that would suit an exoskeleton better. The 137F is a motor used for raising and lowering a standing desk. This motor however has a shape that lends itself well to our application. It is elongated and turns perpendicularly to the rest of the motor, making it a rather flat shaped motor.

This would be ideal for keeping the exoskeleton out of the way of the user and his surroundings as the motor would hug the legs, sticking out nearly half the length of the longboard motors at only 59mm. This would also not require a pulley system and would overall be easier to fit into our design.

We decided to go with the C6374 DC brushless belt motor for multiple reasons. Despite the bulky silhouette that will result from use of this motor, it is the most reasonable. While the 137F would have been ideal, it unfortunately was missing a lot of specifications from the website and had a high stall torque of 24 newton meters.

This would result in the climber having to use an unreasonable amount of force to raise his or her legs. With the 137F aside the two remaining motors were hard to choose between. However, with a much lower price point and a lower weight, the C6374 did not sacrifice much on the performance when compared to D6374. For these reasons C6374 was the most logical choice to make.

For the exoskeleton, it was crucial for us to consider what type of motor, what type of sensor, and what type of motor control board we are going to use to give the exoskeleton the torque to extend the leg and hip joint. Our first decision was to decide what type of motor. After testing different motors and looking at potential motors we decided that we would choose a brushless DC motor due to the availability and the amount of torque that we can provide compared to brushed DC motors and hub motors.

The next decision we made was what type of sensor, if anything, would need to be included with the motor. Since our project has the need to have a significant stall torque, we could not go with a motor that had no sensors on it. We then had to decide between if we were going to use a hall sensor, an optical encoder, or both.

A hall sensor is the cheapest and most space efficient option between the two and would allow the motor control board and the software to have enough of an idea where the motor is turned to that it can provide the stall torque we need. We decided to not include an optical sensor due to the higher cost and space requirements and the fact we were able to use other sensors to know where the leg is extended to instead of needing to invest in an optical sensor. Now that we decided on what specifications we need on the motor we could look online to find the best motor for our needs.

The motor we decided on is a C6374 170KV Efficiency Brushless Belt Sensored Motor for Electric Skateboard Longboarding. This motor is at the desired torque range, if we connect it to a belt drive to gear it down, and has the desired hall sensor. Since the motor is intended for electric skateboard manufacturing, the motor is cheaper and more available than more niche motors.

The team did integrate this motor into the system. The motor worked well with both VESC and the Arduino. The team chose the correct motor to be used in the system.

Pulley System

The motor provides us with a cheap option to connect a belt drive due to the motor having an associated belt drive kit we can connect to the exoskeleton. The table below highlights our top three choices for a pulley system.

Table 3.4.2 Pulley System Selection

Pulley System Selection			
	vanpro DIY Electric Skateboard 83MM	**Flipsky Pulley, keyway, and belt**	**vanpro DIY Electric Skateboard Cruising Wheels PU 80MM**
Timing Belt	285mm	270mm	285mm
Motor Gear	5M/17mm	10mm/16T	15mm/5M
Weight	225 g	N/A	250g
Flywheel	83mm	N/A	80mm

Comparing the 3, the Flipsky was not feasible as it was all sold separately and we could not find reliable information on the product. Also, the flywheel was built into the wheel for this so it would not work for our application. Then the vanpro 80mm was the second best option but it simply was not as good as the 83mm.

The pulley set we chose is the VanPro DIY Electric Skateboard 83MM 90MM 97MM PU Wheel Pulleys Kit Set that provides us with spacers to the exact size of the pulleys, screws also fitting the size of the pulley, and a pulley ratio of 36:18 to provide a torque increasing gear ratio.

For senior Design 2, The team used a custom pulley system rather than a commercial pulley system. The smaller pulley was a 5mm, 16 tooth pulley purchased from Flipsky in order to make it compatible with the motor. The larger pulley was custom designed and 3D printed in order to integrate it into the knee joints. The belt was a 200mm commercial belt that was attached by providing the motor with adjustability. This allowed the belt to be attached then tightened to the required tautness.

Motor Control Board

Now that we decided on the motor, we needed a motor control board that would allow the motor to function properly. We found multiple heavy duty motor control boards that have all the needed connections, a hall sensor connection, a usb input for testing, and a connector to connect our microcontroller to it.

The Comparison chart below represents all types of control boards that we considered when building the exoskeleton.

Figure 3.4.3: Control Board Selection

Control Board Selection			
	Flipsky Electric Speed Controller for Skateboard	**AITIAO PWM Brushless DC Electric Motor Speed Controller**	**ElectronicMaker BLDC Three-Phase Motor Controller**
Control Interface Ports	USB, UART, CAN, SPI, IIC	Terminal blocks	Terminal blocks, GPIO
Hall Sensor Input	Yes	No	Yes
Continuous Current	50A	16A	16A
Instantaneous Current	240A	60A	65A
Input Voltage	20V	5V	5V
Cost	$130	$30	$20
Motor Voltage	8-60V	6.5-50V	6-60V
Board Dimensions	110x40x20mm	123x112x37mm	63x45x31mm

The motor control board we found is the Flipsky Electric Speed Controller for Skateboard FSESC6.7 70A Base on ESC 6.6 with Aluminum Anodized Heat Sink. The added benefit to using that board is that it has three heavy duty capacitors that will help us manage the back EMF of the operator descending down a power pole.

The team for senior design 2 did use the Flipsky Electric Speed Controller. The testing completed used the 4.11 version of the board, while the final assembly used the 4.12 version of the board. This speed controller allowed for the motor to communicate with the VESC software as well as the Arduino. Using a VESC compatible board allowed for the motors to be calibrated and limited by both current and duty cycle prior to using the Arduino. The interface to the Arduino allowed for the motors to be controlled by PPM signals.

On/Off Switch

An important part of maintaining a safe design is having a shut off switch. We decided to have a switch that connects to the wires directly from the battery to use it as a kill switch that can be pressed by a user if anything goes wrong with any component of the exoskeleton as well as if there is any external interference or emergency that the exoskeleton could become dangerous being turned. We have decided to use an electronic switch provided by Flipsky.

The switch is the Antispark Switch Pro 280A for Electric Skateboard /EBike /Scooter/Robots. It is able to handle voltages up to 13S which is higher than the motors we have chosen that are 12S. The button will be placed on the control system box located on the side of the exoskeleton in a place that is very accessible to the user. The fact that the switch is anti spark is very important. If the switch were to spark while inside the control system box it would have a high chance of damaging the motor control board or the microcontroller.

For senior design 2, we implemented a power switch through the power convertor for the Arduino instead. This allowed for an easier integration for the power switch into the system. The switch is discussed more in the battery section.

Battery

From the common battery options of Lithium Polymer (LiPo) and Lithium Ion (Li-Ion), the best option is LiPo. This battery type is the easiest and quickest to charge and also holds the most power in the smallest volume. Based on the 6374 motor it is apparent that we need a 12S battery with a nominal voltage around 44.4 Volts. This will ensure the motor will be running strong. Another property to look out for is the total capacity as we would prefer a battery with more than 10 amp hours, to run the motor for at least an hour with the desired torque.

We compared multiple different battery options and weighed out the needs for our system. The table below highlights the top three battery options and explains why we chose this LiPo battery.

Table 3.4.2: Battery Selection

Battery Selection			
	Electric scooter Lithium ion Battery Pack	**OEM Deep Cycle Li-on 12s4p battery pack**	**Pulse 5000mAh 50C 44.4V 12S LiPo Battery**
Capacity	10 Ah	12Ah	5Ah
Nominal Voltage	44.4 V	44.4 V	44.4 V
Constant Discharge	20 A	20 A	-
Peak Discharge	45 A	30 A	225A
Resistance	-	-	-
Cell Count	-	-	6
Battery Size	220x135x35 mm	50x150x360mm	332x50x47mm
Weight	1.5 Kg	3 Kg	1.5 Kg
Charge Current	2 A	0.5	-
Charge Plug	custom	custom	No connector
Discharge Plug	custom	custom	none
Built in BMS	Yes - 20A	Yes - 10, 20, 30, 50, 80, 100 amps or more	No
Cycle Life		>800	-
Charger	No	Yes	No

After very deliberate and dedicated research we have decided on going with the OEM Deep Cycle Li-on battery pack. This battery pack is far superior than all others considered. It will supply the motor its required 44.4volts at all times, producing ample power and torque. The capacity of this battery also beats the biggest competition with 12Ah as opposed to the 10Ah of the electric scooter battery pack. This means we could run a motor at 12 Amps for an entire hour, or run the motor at 6 amps for two hours.

Testing will need to be done in order to establish the amperage and voltage of the system to maximize power. This battery's sleek and elongated shape allows for an easy installation to the backplate of the device.

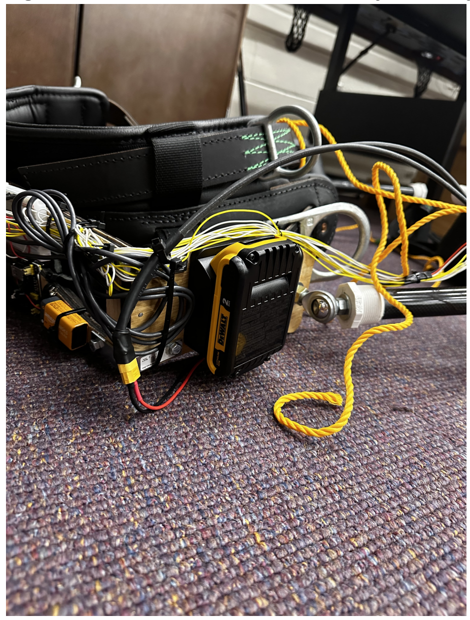
Figure 3.4.3: OEM Deep Cycle Battery

Better yet, we could double the usetime of the device by stacking two of these batteries in parallel bringing us to 24 Ah. This would be easy to do with some modifications to the wiring and would only create a small bulge to the back which would serve as our battery pack. Additionally, this battery pack has a built in BMS (battery management system) to enhance the safety and mitigate risk. Another way this particular model stands out is that it comes with a charger that will charge the battery overnight.

The only downside to this battery would be its heavier weight. Being on the heavier side means we must sacrifice in other areas. However, this battery provides enough power to make up for its heaviness. The weight will in turn be counteracted by the extra force that the motors will generate thanks to the higher amp hours and high voltage.

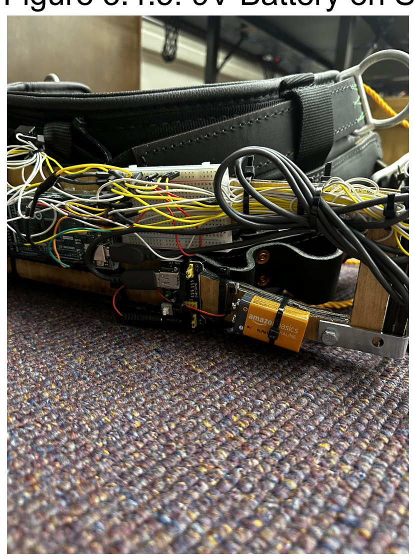
For senior design 2, we used a Lithium Ion battery rather than a Lithium Polymer battery for the final assembly. Two 20V batteries by Dewalt were used rather than a 44V battery. This battery was used because it has been tested and regulated for extended use with a drill, which is an example of a DC motor. The battery also allowed use of a simple adapter that made it much easier to interface the battery to the Motor Control boards.

Figure 3.4.4: Dewalt Battery on System



For Senior design 2, a second type of battery was used to power the Arduino and the peripherals. This battery was used in order to separate the main, high voltage power system from the electronics that were more sensitive to over voltage. The use of a 9V battery also allowed for a simple power convertor to be used and implemented in the system. By using this power convertor, the Arduino and peripherals were also given a power off switch. This allows the user to completely power off and reset the system at any point during use.

Figure 3.4.5: 9V Battery on System



3.5 Design Modeling

This section outlines the various types of modeling software and comparison.

The overall design has been created and designed by the other team, senior design II. There are limitations that require us to have our own modeling option in case we need to make any sort of alterations. The model designed by the other team will be roughly the final design but it does not have any sort of electronic components on it. We are tasked with choosing the parts, and implementing them so we did need to take the design already created and add our components to it.

Another example is if the motor is too big, we would need to change some sizes on the design for the final print so that they can fit. Another reason to have our own modeling design software is so that we can design how the parts will be attached to the exoskeleton. The exoskeleton already designed is strictly just the frame. We did need to design how the parts will be attached to the exoskeleton and the best route to go about that. There are several options when it comes to choosing which designing software we would be using when it comes to altering or creating any part of the exoskeleton. The ones we did be talking about are:

SolidWorks

SolidWorks is one of the leaders when it comes to 3D modeling. It is a computer-aided design and engineering computer program. SolidWorks was designed to work best for windows as Mac devices rarely have support for graphics cards. There are tutorials to run a virtual machine on a Mac device but it is not advised. The original exoskeleton created by the other team was designed on SolidWorks so for compatibility with uploading the design for alterations, this is ideal. Another advantage, when it comes to SolidWorks, is for all University of Central Florida students. We have access to a full free version of the software, so the price is not an issue.

The overall process of SolidWorks is that the user first creates a design with all requirements needed, which could be either 2D or 3D but is preferred for the system to be 2D. Then after you are finished, the model can then take your sketch and make it 3D with all measurements you put. What is also great about Solidworks is that we can design the motors, batteries, etc. Once we are finished, Solidworks allows the user to take their model, in our case the components, and “merge” the file with the exoskeleton file that was built by the other team.

If we did not have access to SolidWorks student edition that is provided by the university, this is one of the priciest programs on the market with today's current price being $7,995. This does not include the “annual maintenance” or in other words, a renewal fee of $1,995 a year. Based on the other team already using this software and our ability to get a copy for free, SolidWorks is a strong contender when it is finally time to decide which software we will be using.

Fusion 360

Fusion 360 is another example of a great 3D programming software. It was designed by Autodesk and is cloud-based. Fusion 360 is primarily focused on free-form models and is established on the cloud. This makes it great for when you are on the move and does not use many computer resources. In comparison to AutoCAD and SolidWorks, the system requirements to use Fusion 360, is roughly a third to a half less. What is great about this software compared to AutoCAD is its ability to stress test our design with real-world conditions. This is absolutely vital as our exoskeleton will be tested beyond measures out on the field.

This is another program we have access to for free. Fusion 360 has a three-year non-commercial copy for all hobbyists or a one-year full-feature version for free for all students. This software is a lesser version of the household names of 3D design but is just as powerful with plenty of strong features to compete. Fusion 360 is cloud-based, allowing this program to work properly on any MAC device as well. If we were not students or hobbyists, the cost to use this program would be $545 a year or $70 a month. This makes it one of the best values on the market.

AutoCAD

The next runner-up in choice of software is AutoCAD. AutoCAD is a similar program to SolidWorks. It is a computer-aided design program for 3D modeling. One of the advantages of AutoCAD is that you can draw your model 1:1 scale. Another benefit is since the main file is created in SolidWorks, AutoCAD has a feature that the files between the two programs are actually compatible and can be opened and used in either case.

This is important so that if we need to make any adjustments to the original file, or if we need to design new ideas such as the motor brackets, we can easily incorporate them together. Unlike SolidWorks, AutoCAD is actually suitable for MAC devices and does not require a virtual machine to work. Since programming on a MAC device works differently, AutoCAD has built the same program but in its own respective nature.

Another great advantage, when it comes to AutoCAD, is the price point. The University of Central Florida has granted its students a free copy of AutoCAD for use. The retail price of this program is $1,865. If we had to purchase this software, it would be well out of our budget that Florida Power and Light are providing. The program does not have a renewal fee.

AutoCAD LT

Another option that is related to AutoCAD is AutoCAD LT. It is practically the same thing just with fewer options. Right off the bat, This version of AutoCAD is “lite” so a lot of the features are missing or are not included. The full version of the original AutoCAD offers 2D and 3D drafting and automation possibilities, but AutoCAD LT only offers 2D drafting capabilities. The LT version has a strong focus on 2D detailing which can be ideal for certain situations. We are building a real exoskeleton so seeing and doing edits to a 3D model is crucial for our needs. This version will also cost us money.

The price to use AutoCAD LT is $460 annually or $60 a month. This price is one of the cheapest on the market, so it was worth considering. The original AutoCAD, we already have for free at our fingertips. This program has its limitations and other various negatives. Unfortunately, we did not consider using it as it does not meet what we would desire.

The table below is a direct comparison of all modeling programs we are considering using.

Table 3.5.1: Design Model Comparison

Design Model Comparison				
	SolidWorks	**Fusion 360**	**AutoCAD**	**AutoCAD LT**
Price per year	$0	$0	$0	$460
UCF Student Discount	Yes	Yes	Yes	No
Owner	Dassault Systèmes	AutoDesk	AutoDesk	AutoDesk
Based	Network-based	Cloud-based	Network-based	Network-based
Stress test Ability	Yes	Yes	No	No
Works on MAC devices	No	Yes	Yes	Yes
2D drafting leader	No	No	Yes	Yes

3.6 Programming Languages

This section will outline various types of programming languages that will be used for our exoskeleton.

After choosing all of the parts and electronics needed for the exoskeleton, we now can move forward to the more tedious part of this build and that is the programming. Simply attaching the motors, batteries, and microcontroller, will not make the exoskeleton work. It needs to be properly wired and have a programming language built “into them” so that they know what to do. There are many scripting languages on the market that can be used for this project. They all have their pros and cons so it is important to take into account all possibilities.

C

Starting with the programming language C. This language was created by Dennis Ritchie back in 1972 with a “general-purpose” pursuit in mind. The reason why this language is still being used today is how fast it processes. It was designed as a low-level language and is faster than some competing programs such as Python. Some examples of popular programs that are mostly written by the coding language C are Linux, Mac computers, Microsoft Windows, and Mobile adaptations such as IOS, Android, and Windows phones.

When developing code for microcontrollers and embedded devices, the C language, and C++ are some of the most commonly used code for this application. In today's applications, C is mainly used for embedded devices and system-level code. It is relatively easy to understand, has access to many different libraries, has fast execution speeds, and with many tutorials and online videos to learn.

This language is difficult but manageable to write and learn the code. The C language is portable and works in multiple computer programs and even has a simple or in other words, “easy” debugging process which will help us out a lot when it comes to programming our microcontroller. When we were first deciding on which language we did use, C was the first in mind.

C++

The following potential programming language we have in mind and is in the same family is called C++. This language was released 11 years after the original language C in the year 1983. This “updated” version of C was developed by Bjarne Stroustrup to be an extension of the C language. With the original C being mainly Low-level, they wanted to create a program that is more flexible and efficient that can also have high-level features. C++ is also considered a

“general-purpose” language but in today's world, it is mainly used for games, search engines, and GUI-Based applications.
Some popular examples are Adobe systems, Apple OS and Microsoft Windows, and the Chrome browser. An advantage of C++ is that C++ is able to run most C code. Unlike C which cannot run the majority of C++. C++ also has the ability to support user-defined data types, unlike C which only supports built-in primitive

data types. C++ also has what most coders use today and that is a variable type called a string.

C++ is one of the most difficult languages to learn as a coder. The reason for this is due to the multi-paradigm nature, or in other words, C++ supports different styles of writing its code. C++ also has a more advanced syntax than other coding languages. Another benefit is that this language is extremely portable and versatile and even has a memory management feather. Massive amount of online learning material and videos that can help make anyone be fluent in this language.

Python

The next language we were considering is Python. This language is the newest out of the three and was created back in 1991 by Guido Van Rossum. The intent was to be the successor to the ABC programming language. The Python language is one of the easiest to learn as it does not involve as much “knowledge” compared to other programs such as C or C++. Another benefit is that Python is free and open source.

There are also plenty of online resources to learn how to read and write in Python code, as well as many videos online as well. Python Code is not actually able to be used in microcontrollers but thankfully to another group for creating a program called “MicroPython.” MicroPython is a full Python compiler and allows this language to be implemented into microcontrollers. A downside to this is that Python is actually the slower language and is not as efficient compared to the others such as C.

The table shown below summarizes some of the major differences between different programming languages that were implemented or considered for this project.

Table 3.6.1: Programming Language Comparison

Programming Language Comparison			
	C	**C++**	**Python**
Year Created	1972	1983	1991
Creator	Dennis Ritchie	Bjarne Stroustrup	Guido Van Rossum
Program File Extension	.c	.cpp	.py
Can run C Programming code	Yes	Yes	No
Supports user-defined data types	No	Yes	Yes
Level	Low-Level	High-level	High-level
Type	Compiled	Compiled	Interpreted
Structure	Structure Oriented	Structure Oriented	Object oriented
Main purpose	Hardware related applications	Hardware related applications	General purpose applications
Must declare Variables	Yes	Yes	No
Pointer Available	Yes	Yes	No

Built-in functions available	Limited	Large	Large

For Senior design 2, we did use the C programming language to complete the software of the lower body exoskeleton. This was used in concurrence with the Arduino system and development environment. The use of C and the Arduino allowed for multiple important libraries to be used to interface with Serial communications, the motor control boards, and the sensors. A sample of the completed program is shown below.

Figure 3.6.1: Final Software Section

full_exo_code.ino

```
#include <Wire.h>
#include <Servo.h>

// Speed Controllers
Servo LeftESC, RightESC;

// ESC Signal Pins
const uint8_t LeftOutputPin = 5;
const uint8_t RightOutputPin = 6;

// High, Neutral, and Low signals in Microseconds
const uint16_t H = 2000;
const uint16_t N = 1500;
const uint16_t L = 1000;

// Motor step size
const uint16_t STEP = 500;

// Accelerometer values
long avg_accel;
long x_accel1, y_accel1, z_accel1, total_accel1;
float gForceX1, gForceY1, gForceZ1;

long x_accel2, y_accel2, z_accel2, total_accel2;
float gForceX2, gForceY2, gForceZ2;

long x_accel3, y_accel3, z_accel3, total_accel3;
float gForceX3, gForceY3, gForceZ3;

long x_accel4, y_accel4, z_accel4, total_accel4;
float gForceX4, gForceY4, gForceZ4;

// gravity constant
float g = 9.81;

// fall detection counter
int count = 0;

// Angle calculation variables
float leftAlpha, lastLeftAlpha, leftTheta, lastLeftTheta;
float rightAlpha, lastRightAlpha, rightTheta, lastRightTheta;

float upDeltaLeft, downDeltaLeft;
float upDeltaRight, downDeltaRight;

```

3.7 Facilities and Equipment

This subsection outlines all the locations that we are utilizing in order to build the exoskeleton and the equipment needed.

When designing and building an idea from scratch, especially one as complicated as an exoskeleton. There are many moving parts from start to finish that we would need to be successful by our deadline. The first is the facilities. We needed a facility in order to conduct the day-to-day operations and meetings so that everyone involved knew what they were supposed to do and to keep everyone on track. We first began with Zoom online meetings but quickly came to a realization that in order for us to really keep the ball rolling consistently, we needed to have weekly in-person meetings.

We opted for various locations at the University of Central Florida such as the John C. Hitt Library but it was constantly crowded. We tried the first floor of the Technology Commons building as there was a whiteboard but there was the same issue of the constant crowding and it was tough to book a room for us to discuss. Our last and best option which we still use today is an office in the Military and Veteran Success Center. There we were always able to have a room to ourselves at our disposal and were a great place to conduct our day-to-day operations.

The next facility that we did utilize is the Manufacturing Lab which is also conventionally located in the Engineering building at The University of Central Florida. The design that was already created by the Senior Design II team, is finally time to begin building the exoskeleton. Since the main exoskeleton will be made out of aluminum, we decided that it would be best to test it first. Instead of milling the entire exoskeleton and "hoping for the best." We wanted to first for our testing purposes, simply create a portion of the exoskeleton, in our case we wanted to start with the knee joint.

To achieve this while keeping costs as low as possible, we decided to take advantage of our Manufacturing Lab which is available to all students. Here is where all 3D printing and other various applications happen. We first recreated the knee joint as plastic to test our motors and make sure that the output numbers align with our theoretical ones. When they do align or close enough, we then begin the process of officially creating the exoskeleton as metal. What we did was take the SolidWorks design that the Senior Design II team has made, isolating only the knee portion to be 3D printed, and then converting the file type to ".STL" file so that the 3D printer can read the file and print out our knee joint.

The third and final step is to finally build and assemble the exoskeleton. After purchasing the metal and various other components (Discussed in the next section 3.8 Consultants, Subcontractors, and suppliers.) It is now time to use the Machine Shop which is also located in the engineering building at the University of Central Florida.

At this location the price is very reasonable for students. What we would do is upload files of different sections of our exoskeleton to have it be custom cut and fabricated for our needs. In this shop they have a large range of tools such as milling machines, drill presses, a band saw, metal shears, lathes, and other assorted tools and machines. For the students that want to learn how to machine shop, they even offer training classes for those interested but have a priority for Mechanical and Aerospace Engineering (MAE) students.

The table below compares all facilities that we used during our senior design I project.

Table 3.7.1 Facilities Comparison

Facilities Comparison			
	Military and Veteran Success Center	Manufacturing Lab	Machine Shop
Cost per Hour of Use	$0	$40	$35
3D Printing Available	No	Yes	No
Metal Fabrication Available	No	No	Yes
A Room for Meetings	Yes	Yes	No
Time Open	9:00 AM - 5:00 PM	8:00 AM - 5:00 PM	8:00 AM - 5:00 PM
Days Open	Monday - Friday	Tuesday, Wednesday, and Thursday	Monday - Friday

For senior design 2, we mainly utilized the following: Innovation lab, Machine shop, and the senior design laboratory.

3.8 Consultants, Subcontractors, and Suppliers

This subsection outline all consultants, subcontractors and suppliers that we used to build the exoskeleton

Now to discuss more about the “communication” side of our project. We have been in close contact with our main advisor Rich DeBear. He is the one in charge and is the one overseeing this entire project. He has also been working with the other Senior Design team and has decided to make this be a legacy project. What this means is that it has been approved to have another semester of Senior design I students join the project for the continuation of the overall success of the exoskeleton that we are building. Since the start of the semester, there have been weekly meetings every monday evening to go over anything that has needed to be discussed. Such as, approvals for the purchasing of anything related to the exoskeleton, weekly progress reports, any questions that we may have or need help with anything, any form of support that can lead to the success of this project within a timely manner.

With this project being sponsored and made for the Florida Power and Light Company. We also have a sponsor directly from the company, Kyle Bush. Kyle is one the engineers working for the company and is our direct connection to all specifications and desires that Florida Power and Light Company would like to see from the exoskeleton. This connection is absolutely vital for the overall completion of the project as they are the ones that guide us towards their vision and are the ones paying for this project as well. We started this semester with a weekly meeting on Zoom with Kyle early midday but eventually led to us transiting over to a meeting every other week. Kyle is the one to answer if we have any questions directly towards the company or need help with the exoskeletons requirements.

When it comes down to the actual suppliers, we have used various ones across the board. The parts that we have selected from certain suppliers are all subject to change as more development is made with the exoskeleton. We do have a strong confidence that these will be the final parts or at least maintain relationships with these sellers to find similar parts in the case we need a different option.

Metal

The most important part of this exoskeleton is choosing the right type of metal and manufacturer. There were many different suppliers that we could have chosen but decided on using a company called OnlineMetals. This company has any size imaginable and relatively fast shipping which increases favor for this company. Another benefit is that their prices match any competitor. In future developments we could still change suppliers but for the time being and based on our research, we did use this company.

Motor

We have decided to go with a company that we found off of Amazon. The supplier's business name is Emic and they sell all sorts of different tools and products in this space. The specifications that the motor also provides were very similar to what we were looking for. The other great benefit to using this seller is the reviews, there are many strong reviews that backs up that product and the reputation of the seller so we felt confident that what we were buying was high-quality motors for a great price. Another strong benefit is Amazon's policies. They have very fast shipping (less than a few days) and also a very generous return policy.

Pulley System

Another necessary item that we needed for this build is the pulley system that will allow the motors to move the exoskeleton. This was actually a difficult thing to find because we wanted it to match the same size as our motor. We were able to find one from a company called VanPro. Another vendor on the Amazon website, They specialize in all things electronic and have the pulley system that we desire. This company also has very strong reviews and a great price point. Being based on Amazon as well, there is a very generous return policy and fast shipping. Many competitors that we saw were well over twice the price and shipping would take two to three times longer to arrive.

Motor Controller

For our first phase of this build, we did build the knee joint of the exoskeleton so it is important that we have all components necessary for it. We did need a Motor controller to help adjust the motor, and we were able to find a supplier called ElectronicMaker. This brand specializes in a wide variety of electronic components to other fields of sales. Now this brand has relatively low reviews, we are still confident in this product as it is being sold on Amazon and with its strong policies, we have nothing to fear.

Speed Controller

The final piece of the puzzle to have a working knee joint is the speed controller. This part is a little bit more expensive than everything else but it is very necessary. It is sold by a supplier named FLIPSKY. This brand specializes in motor technology and various electronic components. This is yet another item being sold on Amazon that has great reviews and fast shipping. We are confident in all of our product choices and the pace that we are going.

3.9 Build, Prototype, Test, and Evaluation Plan

This section outlines the plans and results of benchtop testing as well as the plan for the build, test, and evaluation of the prototype and full system implementation of the design.

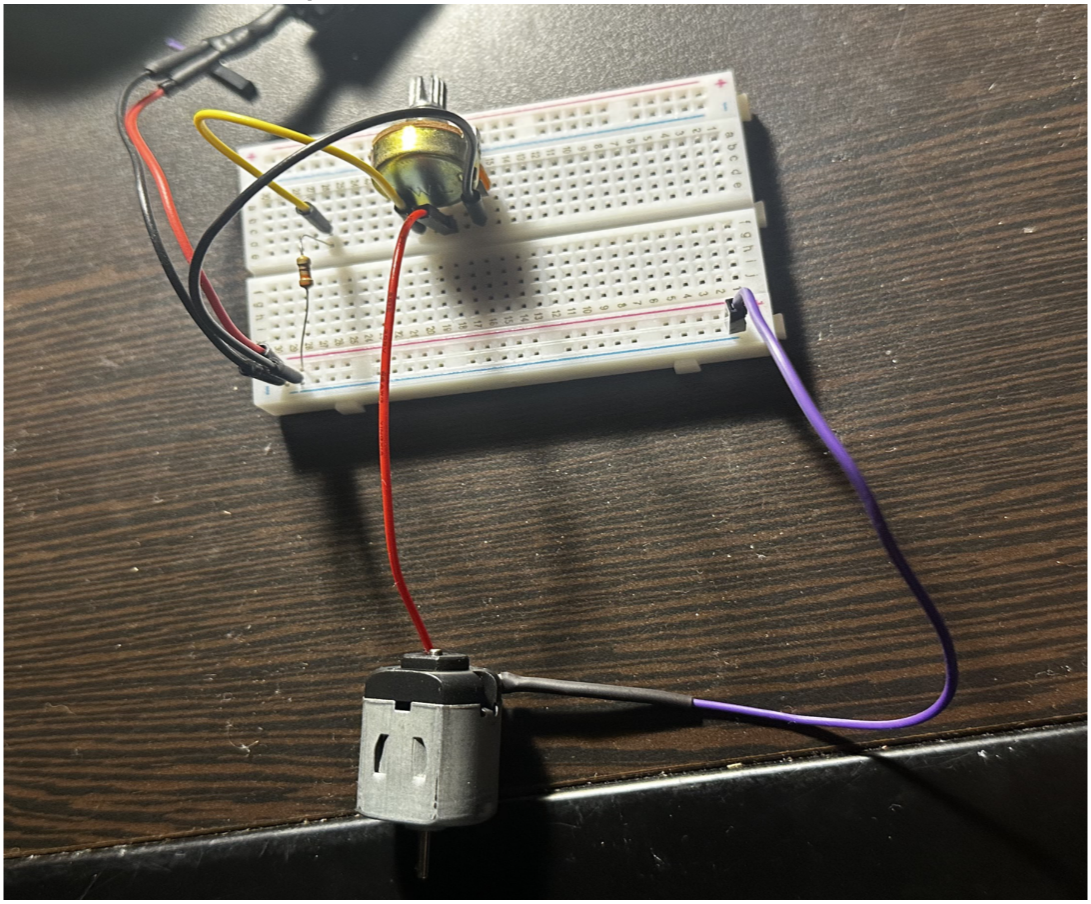
Benchtop Testing

After the components arrive, they must be tested prior to being built into any higher assembly. The parts are able to be tested using the same strategy as the initial component testing. The benchtop setup that was previously used was modified in order to incorporate the real parts that were purchased. This required changes to the stand that holds the motor to accommodate the size of the new motor. The motor control board was also swapped out. We were able to procure a wide variety of motors, motor control board, and microcontrollers to test in various combinations. In these tests we were able to understand how each component operates and the limitations of each component in different situations.

DC Brushed with constant power and potentiometer

This test included applying a constant 5V to a breadboard containing a potentiometer used to power a small DC brushed motor. The test was necessary in the early testing stages to understand the basics of powering this type of motor. The potentiometer allowed for variable current draw which greatly impacts the torque output of the motor. This allowed us to understand how changing resistance can impact the torque output of this type of motor on a small scale.

Figure 3.9.1 Small DC Brushed Motor Test



DC Brushed with planetary gearbox attached to 3D printed knee

During this test we were able to procure the MAE team's design for the knee joint and 3D print it into PLA plastic. With that prototype joint, we were able to test the amount of strain placed on the joint with a direct motor mount. For the motor setup, we used a DC brushed motor with a planetary gearbox.

For the testing phase, we supplied power to the motor and observed how much force it could provide at differing levels of resistance from the potentiometer. Another observation we made was that the size comparison between the motor and the joint needs to be considered. This motor was much too large, length-wise, to use unless we utilize a 90 degree rotating gearbox.

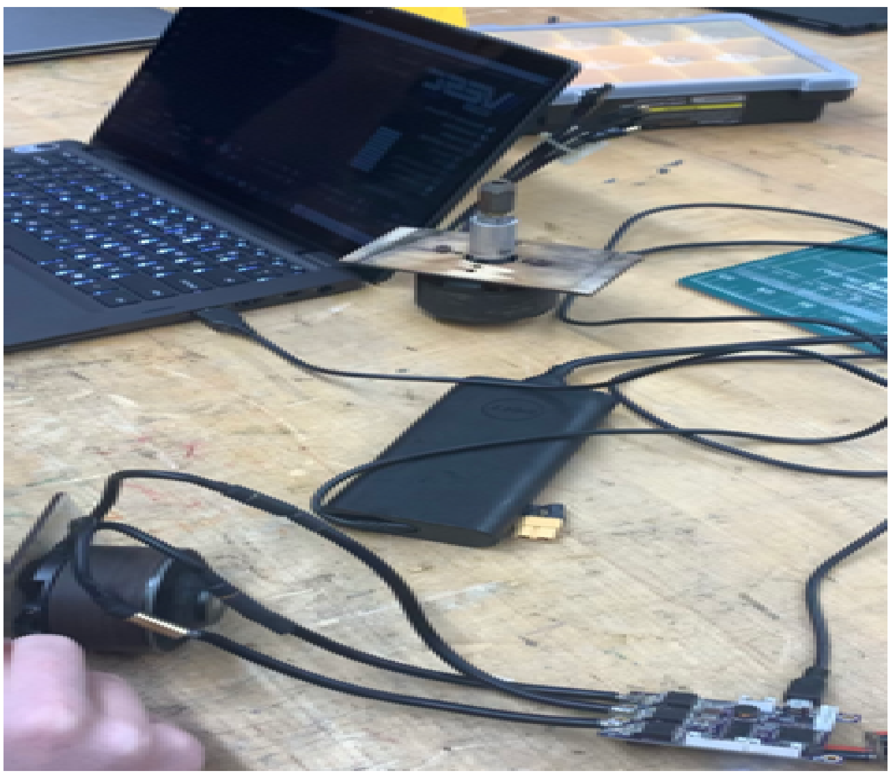
Figure 3.9.2 DC Brushed Motor Test with 3D Printed Joint

Brushless DC motor Connected to Motor Control board and VESC tool

By utilizing the UCF innovation lab we were able to get access to an electric skateboard motor that we could test with a motor control board and motor control software. Once we connected the motor cables to the motor controller, we connected a micro usb to the motor control board. By using the VESC motor control software, we were able to get the motor to work initially.

To increase the effectiveness of the motor, we needed to calibrate the motor to the software. We inputted the size of the motor, the voltage and current rating, and other specifications found on the motor's data sheet. By calibrating the motor, the software was able to have a better understanding of where the motor is. We were unfortunately not able to get a hold of a motor with a hall sensor, so the motor was not as effective at producing stall torque. Though, when we measured the stall torque on a motor without calibrating and a motor with calibration, we found a significant difference in the amount of stall torque it could provide. Without calibration, we could hold the motor in place with very little force. When we calibrated the motor, the amount of force to stall the motor was significantly increased. This test allowed us to get more experience working with larger brushless DC motors. We also learned more about the kind of software that can be used to calibrate motors to provide them with a higher stall torque.

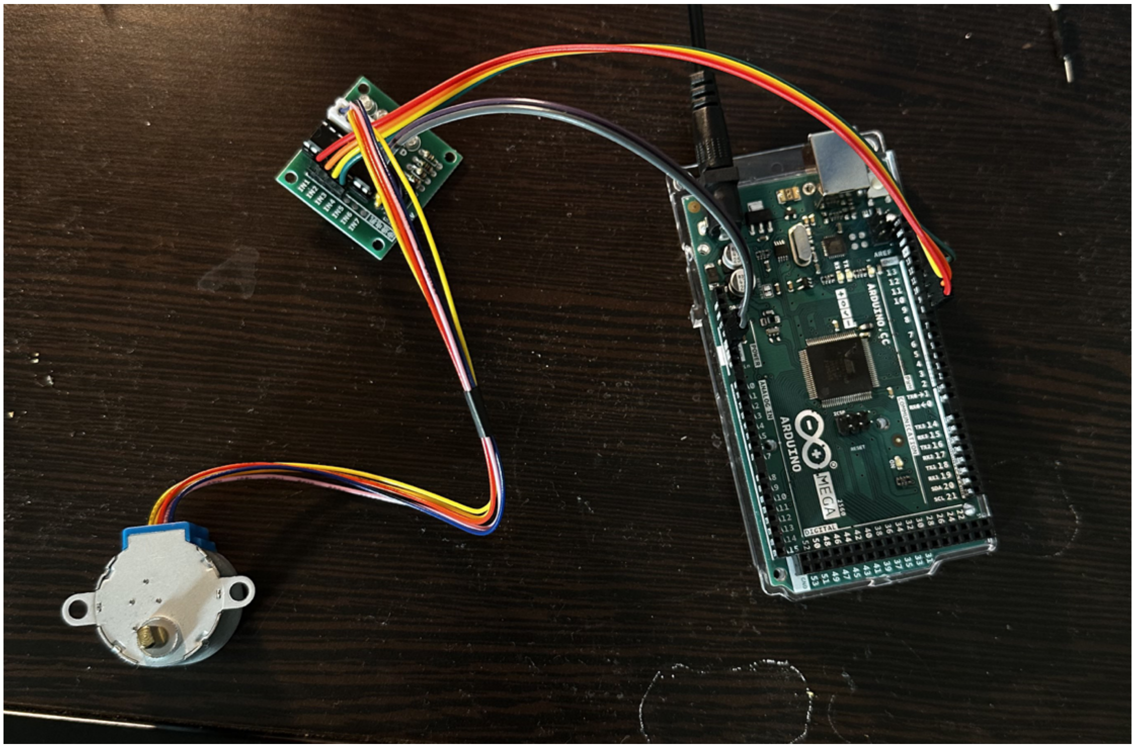
Figure 3.9.3 DC Brushless Motor Test with Software



Stepper with arduino mega and control board

This test consists of a stepper motor connected to a motor control board and an arduino mega. This benchtop test allowed us to gain an understanding of the capabilities of the arduino mega board. This arduino board is on the higher end of processing power we can utilize for the arduino brand of microcontrollers

Figure 3.9.4 Small Stepper Motor Test

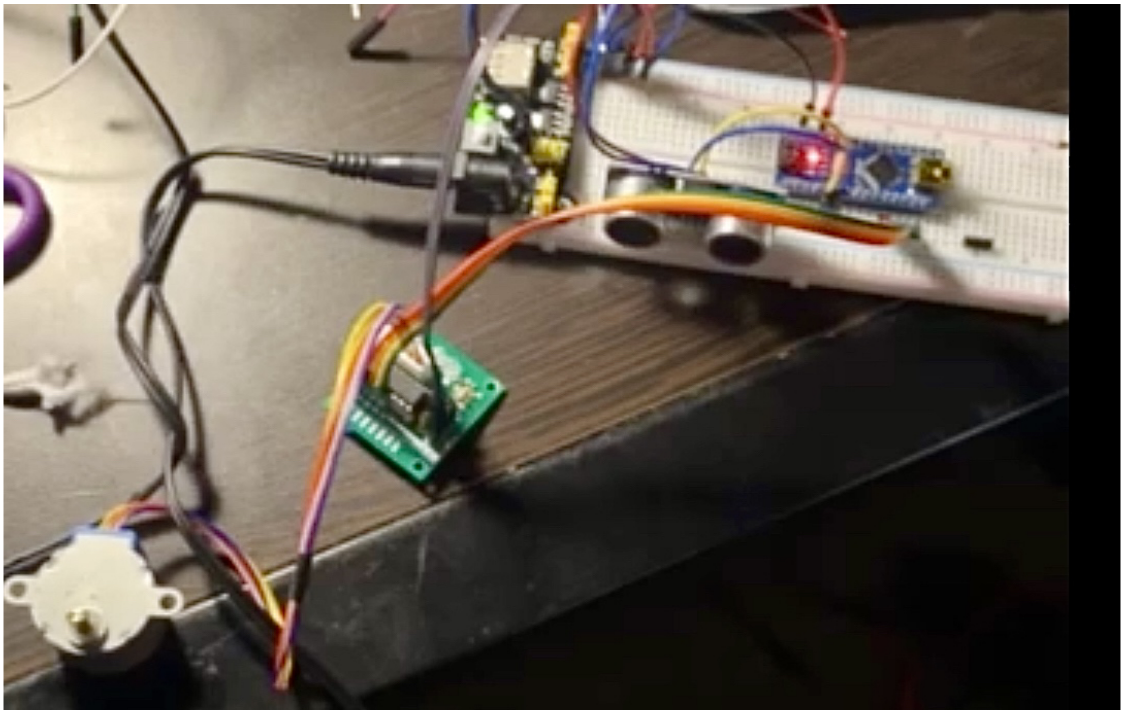


Stepper with arduino nano, control board, and ultrasonic sensor

This benchtop test consists of a stepper motor with a smaller and cheaper motor control board. The board is connected to an arduino nano with an ultrasonic sensor. The purpose behind this testing is to see the drawbacks of using less expensive motor boards and microcontrollers. The reason we were able to use the smaller devices is due to the less complex nature of the stepper motor. We also used the ultrasonic sensor to both simulate any sort of sensor device as well as test the capabilities of an ultrasonic sensor to see if that type of sensor could be of any use to our design.

From this benchtop test we found that when using a stepper motor it was possible to use a more simple arduino board and motor control board, but we were using its full capacity for only one board. This motor control board would not have worked for a brushless DC motor and only a stepper motor. We found from this testing that the stepper motor would not provide enough speed to allow the exoskeleton to express fluid human movements when ascending a power pole.

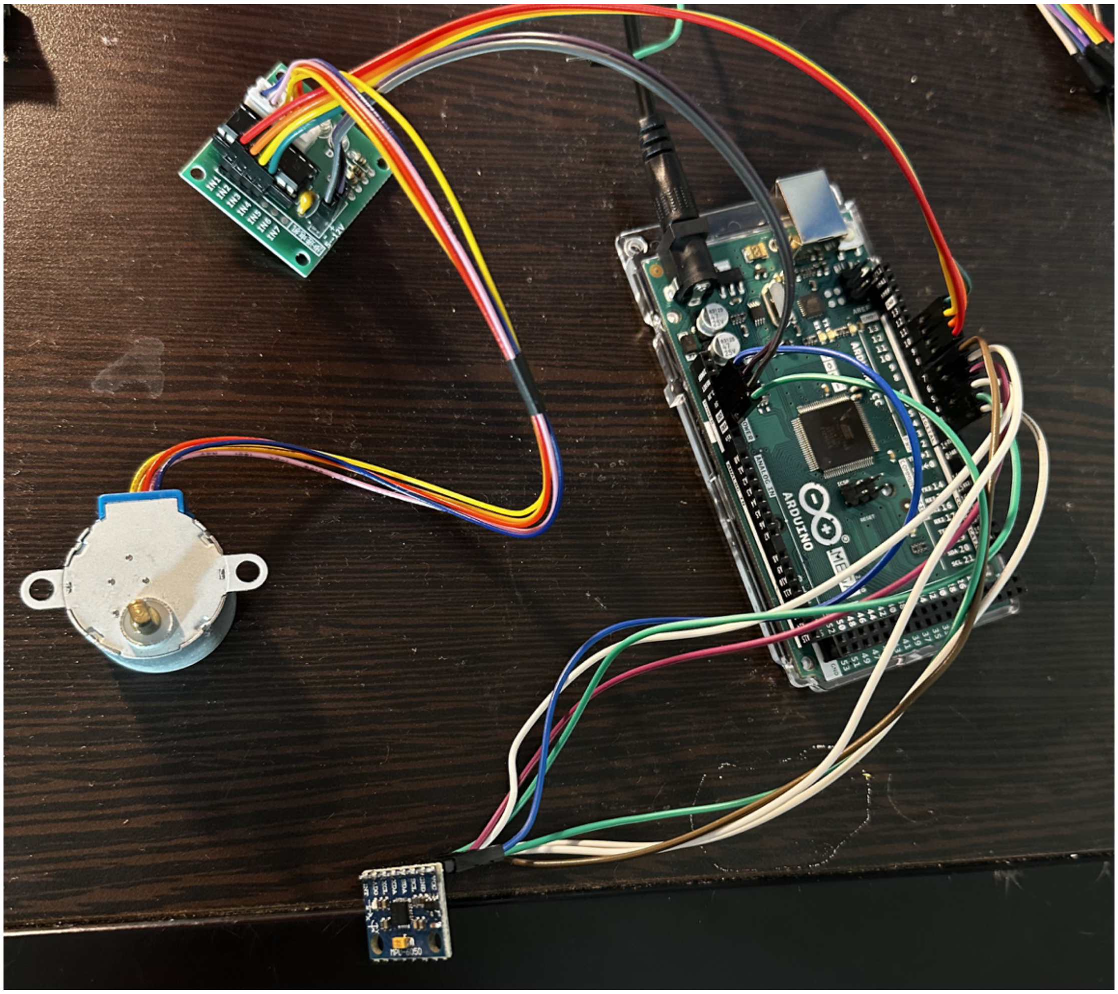
Figure 3.9.5 Stepper Motor Test with UltraSonic Sensor



Stepper with arduino mega, control board, and accelerometer

The test shown below gave further testing with the stepper motor and Arduino Mega. The important component that was added to this test is the accelerometer as a sensor input. The accelerometer is a very common sensor to use to help track motion and movement. This is why the component was in such strong consideration to be used for the exoskeleton's main sensor to sense human motion. The test feeds responses from the accelerometer to the Arduino. When the accelerometer senses a significant motion, the motor should move. This is done to help simulate how the real system will react to human motion to tell the motors when to turn on and assist the user.

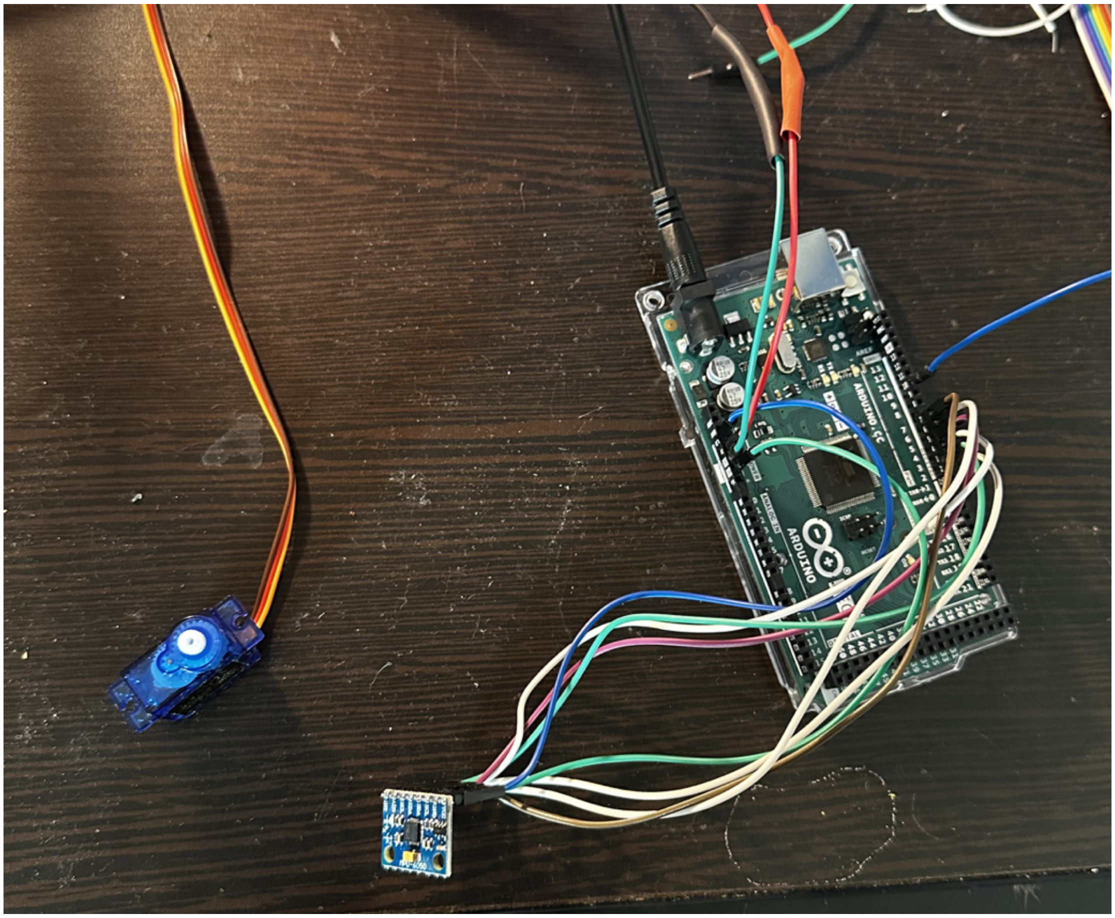
Figure 3.9.6 Stepper Motor Test with Accelerometer



Servo with arduino mega, and accelerometer

The test shown below is very similar to the previous test implementing the accelerometer. The difference in this setup is the type of motor being used. This test helps the team to understand how well each type of motor responds to input from the accelerometer. This test also allowed us to understand the capabilities of an accelerometer and how it can be inputted into a microcontroller. This test allowed us to see how the arduino mega board was able to handle taking input from a sensor and using that data to determine when to turn on and off the motor. We were also able to test how responsive the arduino mega and the accelerometer were to know if responsiveness would be an issue if we utilized an accelerometer for the exoskeleton design.

Figure 3.9.7 Servo Motor Test with Accelerometer



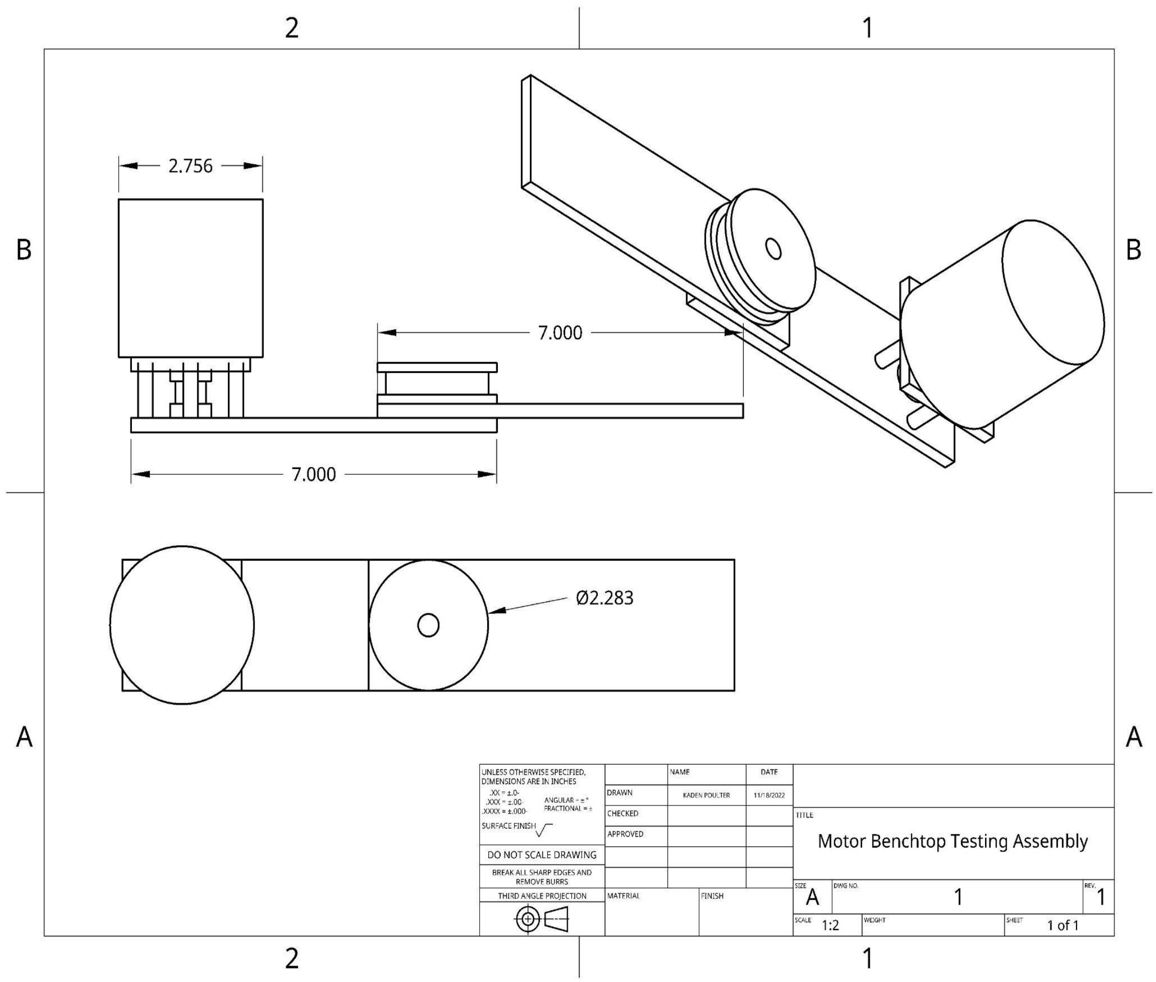
The other major component that was integrated into the benchtop testing was the pulley system. This system was specifically designed to function with the motor, so there was no added work to connect the motor and pulley system. Attaching the new pulley to the benchtop itself was as simple as drilling new holes and using the spacers that came with the pulley system.

Testing is a broad term for a large amount of work to be done. Since our lower limb exoskeleton has so many powered and moving parts, we must ensure they all work in unison. Starting with the battery, there is no room for error, and connection must not be lost within the system at any time. This means we were experimenting with brands of wiring until we found what would suit our battery best. On the control board, the software has to be flawless, without any faults, as the entire system depends on what the control board outputs.

To test this most benchtop testing can occur while connected to a computer, by studying outputs based on given inputs. Next the motor must be proven to work in unison with the battery and control board. It is necessary to maximize power and optimize performance as well as ensure proper operation based on inputs. Putting this all together is the pulley system, responsible for converting the electrical power generated by the battery into mechanical power that moves the leg. This pulley system must be tested to be fully compatible with the motor as it is the final leg of powering the exoskeleton.

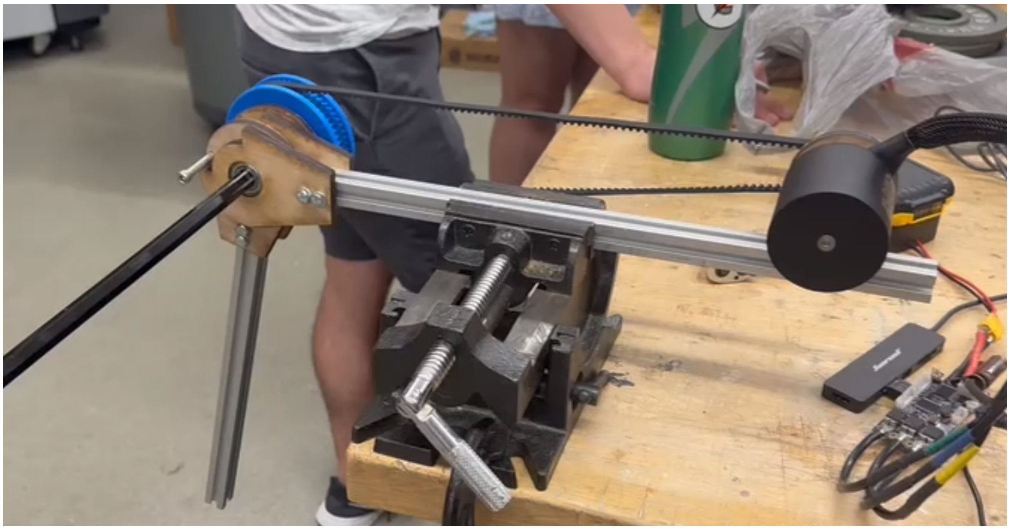
The figure below shows the 3D model drawing of the test bench that will be made of ¼ inch aluminum and allow us to test our motor with different gear ratios using pulleys that will be 3D printed.

Figure 3.9.8: 3D model drawing of test bench



The team completed benchtop testing with the intended setup. This test provided key specifications in order for the final build to be completed. The maximum current, the maximum duty cycle, the stall torque, and the current draw for the system were discovered from the test.

Figure 3.9.9: Test Bench Setup



Prototype Build and Test Plan

The components can be built and tested at a subassembly prototype level after passing through the benchtop testing. The subassembly under test is a knee joint. This prototype will be 3D printed rather than the aluminum material being used in the final build. This is due to the manufacturability of 3D printing compared to metal machining. There is a parallel effort being led by the MAE team to get the real metal joint, as well as the rest of the frame and joint pieces, machined. The prototype will be powered using a power supply rather than a battery because the battery is being ordered after the other components in order to test prior to choosing a battery.

During the prototype phase test, we plan to first test if the motor's mounting is correct on the knee joint designed by the MAE team. Assuming the motor is adequately secured to the joint, we did move on to test the motor's provided torque by first attaching the joint to a table using clamps or straps. Attaching the joint to a table initially versus going straight to attaching it to a leg is due to safety concerns.

During that testing we did be able to calibrate the motor, the hall sensors, and motor software to the specifications of the joint. Though, due to the prototype being most likely made of PLA 3D printing filament, we were not able to stress test the joint to the capacity when it is made of a harder material such as aluminum. We were able to stress test the connecting bolts, belt, pulleys, and spacers to ensure that they will not break or become distorted from the applied forces. We did then attach the load sensors and accelerometers to a teammate's

leg to simulate if the knee joint was on the user’s leg and ensure that the sensors work properly both activating the motor when needed and deactivating the motor at the right place to avoid hyperextension.
Once there has been suitable testing to ensure the design is properly calibrated and we understand certainly how much force will be provided at the current motor settings, we did move on to the second phase of the prototype testing. we did attach the knee joint to the knee of one of our teammates and perform a series of movements. Those movements will range from climbing a ladder, to squatting down. Each of those movements will be done with and without power to also understand how much back EMF force the user will feel during the exoskeletons powered off state.

To ensure the safety of the user during the testing phase, we did have the motors connected to a power supply with a person on standby to shut off the power incase of any mishaps with any component of the exoskeleton. Initially the motor will be activated without the use of the sensors to ensure safety, but once we have double checked that the motor is working properly and the sensors are working properly we attach the sensors to the user and compose a full test. During that test the user will perform the same movements (climbing a ladder, squatting, etc.) and convey and record how much of the overall naturally produced force required for those motions has reduced.

Build Plan

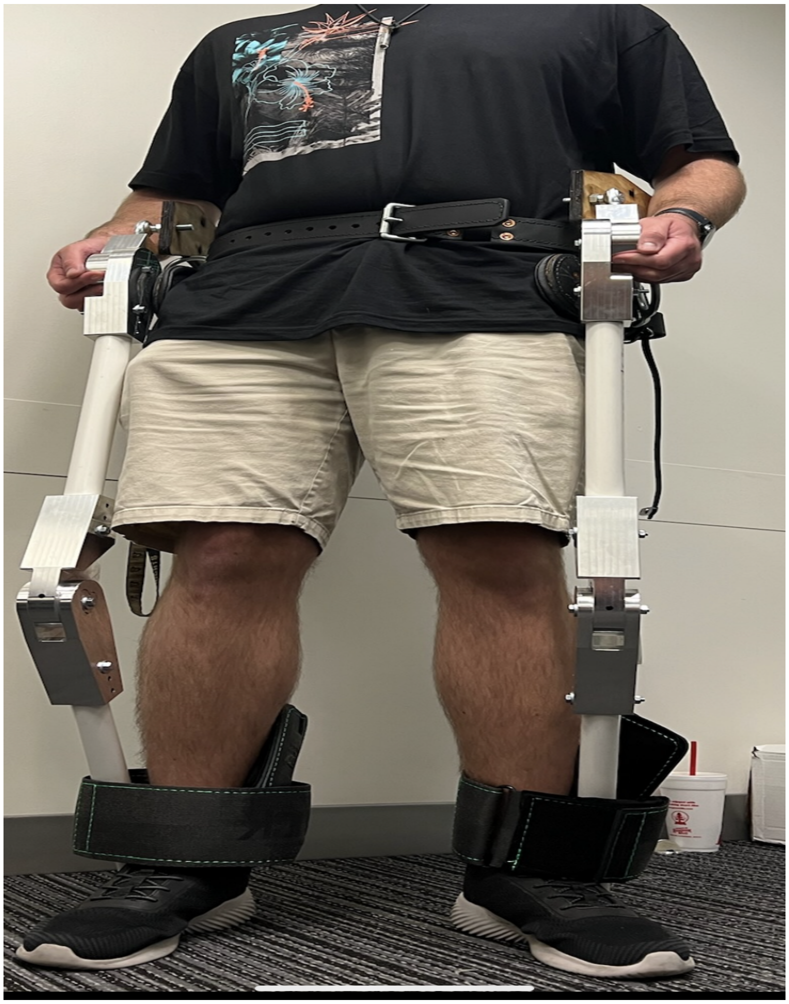
The prototype must be assembled strategically to reduce the risk associated and build a successful exoskeleton. The initial joint that was prototyped was the knee joint. The prototype build utilized the knee motor, knee joint design, bearing implementations, and motor mounting system. This 3D printed design will be recreated using the aluminum design rather than the plastic. Once each part is procured, we begin by assembling any components of the exoskeleton frame that require assembly. The joints will first require bearings to be placed on the axis of the joints. The joints will then be assembled together and ensure each connection is secure. Then the joints will be attached to rods on each side and secured using the custom pins. Then the legs will be attached to the waist plate using heavy duty bolts. Then we connected the foot plates to the bottom of the leg to add the final part of the frame.

Once the frame is assembled we double check that each connection is secured before adding the electrical components. We did first attach the motors to each joint by first attaching the pulleys, spacers, and then the motors to the spacers. Each motor component will be ensured for stability and that each connection is properly connected and secured. We then assembled the battery pack with the batteries, the battery charging board, and the casing that will have thermal dissipation methods inside of it. We then connected the battery pack to the back of the waist plate since the waist plate will be designed for the batteries to come off and on to be charged. We then attached the control system to the side of the exoskeleton above the hip.

The control system includes the microcontroller, the power distribution board, and the switches to turn the system on and off. The casing for the control system will be 3D printed and each board will have its designed place that can be connected using screws. Once the boards are in place, we can attach all the connectors and switches to their mounting holes and attach all the wires using solder. Then we did place both the accelerometers and the load sensors in their desired locations. Once the control system and sensors are placed on the exoskeleton, all the electrical components will be checked to ensure every connection is secure. We then began connecting the wiring from the batteries to the control system. Then we connected the wiring from the control system to the motors. The last wiring required is to connect wiring from the control system to the sensors.

The image below shows the first stage of the prototype exoskeleton frame that we were starting to test with. This prototype contains the first iteration of the mounting system for the electronics.

Figure 3.9.8 Exoskeleton Frame Prototype



Test and Evaluation Plan

The exoskeleton must be tested as a complete system after the assembly is complete. There are many components that go into the frame, control system, and joints that have completed component, benchtop, and subassembly level testing, but the components must now function as a system. A number of tests and metrics will be taken in order to verify the functionality. The system must also be tested similar to a benchtop level test prior to being tested on an actual person.

This is done because of the amount of risk associated with having electronic motors provide force on a knee joint that can overextend and injure the user if not properly tested and calibrated. Though, since the exoskeleton is fully assembled we did not be able to clamp it to just a table. We did create a fake lower body using wood and cloth to test the initial usage of all the motors at the same time with the sensors detached from the frame and placed on one of our team members to simulate the sensors being on the actual exoskeleton.

With that set up we did a test to ensure the motors are activating when we desire them to as well as if the motors stop before attempting to hyperextend the knee joint. We were also able to test how using all four of the motors at the same time affects the control system and battery to ensure without any doubt that the exoskeleton is safe for a user to wear. We have created a checklist of things we can test for during this phase of testing the fully assembled exoskeleton.

First we did have the person with the sensors on them raise and lower their leg to ensure the responsiveness from the sensors to the motors is adequate. We then had the person squat down to activate all the motors at once ensuring there is no issue with provided power or software. Then we did some fast paced squats and jumps to test the limits of the responsiveness of the whole system to ensure they are above what a human can produce.

Once the required tests were done with the faux lower body we were able to move the exoskeleton onto one of our team members. From there we did begin with the motors set to a low current and low torque mode for safety. The user will begin to move their leg up and down as an initial test and record how responsive it feels once it is on a human leg. We then have the user climb up a set of stairs with the exoskeleton on and record how much force was needed to be exerted by the user versus normally climbing stairs.

Then we did have the user climb a ladder and record how much easier it is to ascend and descend the ladder. Then after we have tested it fully on one person we did switch to another person of a different height and weight to adjust the exoskeleton for a different person. We did conduct the same tests as before to ensure the exoskeleton is accessible to all body types.

If we are given the opportunity after initially testing in a controlled environment, the next step would be to acquire pole climbing equipment and ascend and descend a pole. In this test we would acquire the rope that goes around the pole and attach the spike onto the foot of the exoskeleton. We did ensure we have a cushion underneath whoever is testing on the power pole and climb to a safe distance initially and then descend. By doing that we would be able to test how the exoskeleton reacts to being in a hot and humid environment and how much exertion and strain it prevents when doing its desired task.

For Senior design 2, The team completed the final build of the lower body exoskeleton. This was done by following the plan and using the components discussed earlier. The final assembly was tested on various capabilities. The system was first tested on its mobility and ergonomics. The testing showed a user is able to move freely in the exoskeleton to complete the expected job. The system was then tested on its responsiveness when climbing. The sensors and motors responded correctly in order to assist the user. The final test for the assembly was a full system test during the intended application. A full climbing test was completed to test the system in an environment similar to how it would *be seen on a job site. The lower body exoskeleton final assembly completed and passed all expected tests.*

Figure 3.9.8 Exoskeleton Full Prototype

Contingencies

While building an exoskeleton from scratch, we are making sure to double-check our work every step of the way but there can be many unexpected problems that can arise. We as senior design I students, are put on a strict deadline to have this project completed so we have our mentors that can help along the way. Our main advisor Rich, if there are any immediate problems we are to report them to him as he is the one that can best guide us on resolving an issue that is out of our control.

If there was an issue that was to arise due to a problem with one of the components, we would try to get it replaced as soon as possible. If the replacement will cause us to miss a deadline or push us back heavily, we did reach out to Rich or to the team over at Florida Power and Light about the situation. Also, if the motors, for example, do not provide enough torque or for any other reason. We did return to the drawing board and started testing and equating for a proper replacement.

If Florida Power and Light do not like the exoskeleton that we build or if there are any issues that they do not like and we are running out of time. This project can be moved as a “legacy” in which another senior design I team can be assembled to continue on the project.

4 Design Constraints and Standards

This section contains information on the common standards that are relevant and the constraints that needed to be in discussion.

4.1 Related Organizations and Committees

International Organization of Standardization

International Organization of Standardization is known as ISO and sets many relevant standards in engineering. The organization has helped create over 20,000 standards regarding terminology and methodology. These standards cover almost all types of technologies and are accepted standards in 167 countries. Part of ISO are the hundreds of Technical Committees, referred to as the ISO TCs. Technical committees are the bodies of experts who come together to create and publish the standards.

International Electrotechnical Committee

The International Electrotechnical Committee is responsible for preparing and publishing international standards for electrical technology. The IEC began with its inaugural meeting in 1906. Since then, the IEC has been a crucial part in developing standards for technology. Their most notable standards for measurement are the gauss, hertz, and weber units. The IEC also played a large role in developing the International System of Units (SI). The IEC also is responsible for creating a multilingual international vocabulary for terminology related to electrical technologies which resulted in the Electrotechnical Vocabulary. The IEC was originally located in London, it is now based in Geneva, Switzerland as of 1948. The IEC is composed of members from 88 countries all over the globe.

ASTM International

ASTM International, previously known as American Society for Testing and Materials, is an organization that creates and maintains a type of standard known as consensus standards. Consensus standards are developed and maintained by consulting any parties that are expected to be involved or have a staked interest in the standard. These are recommendations and best practices provided by experts in the various fields. Consensus standards cannot be enacted by themselves and must be presented to and accepted by a governing or regulatory body. The Occupational Safety and Health Association is a major organization that commonly uses consensus standards to help dictate and define their standards.

4.2 Related Standards

ISO TC 299 Robotics

The ISO TC 299 is a standard regarding the use and application of robotics outside of military or toy applications. The standard is designed to improve safety and innovation in robotics used in industrial and service applications. ISO TC 299 defines important terminology such as an industrial robot and robotics system. It also outlines key measurements and commutability in the performance of the robotics systems. The standard also outlines how to properly and efficiently implement industrial and service robotics into various industries and applications. By standardizing robotics interfacing, performance, installation and other key factors in their development, there is able to be safe, clear, and best practices in the field.

Impact of ISO TC 299 on Design

ISO TC 299 is the standardization in the field of robotics, excluding toys, and military applications. According to ISO 8373 a robot is defined as any actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks. By this definition our lower limb exoskeleton falls under the category of robot, more specifically an industrial robot. As our system will be deployed for use in the field for use by linemen. The next meeting of Technical Committee ISO 299 will be held in December of 2022 between the twelfth and sixteenth. The outcome of this meeting will have a direct impact on our design with regards to the safety and use of our product.

ISO 8373 Robotics vocabulary and Characteristics

The ISO 8373 standard provides a clear definition for each robotics term to ensure clear communication when talking about robotic products. The standard clarifies the difference between industrial robots, service robots, and medical robots to ensure any robot being designed will be called by a name that is referenceable to a standard. These definitions are meant to be followed by anyone developing robotics.

Impact of ISO 8373 on Design

This standard is important for us to understand to ensure any robotic components we discuss correlate correctly with this standard to avoid any miscommunication. This also aids in how we can classify our device based on whether it is autonomous or not. For example, the current design by definition is a robot due to there being an autonomous component with the motors activating using sensors rather than user input. We did also utilize this standard when discussing the electrical and mechanical components of our design to ensure our terminology is accurate when discussing within our team and with other professionals.

IEC/EN 60034-30-01 International Electric Motor Efficiency Standards

In order to initiate the efficiency classes for electric motors produced from all around the world, the IEC developed the IEC/EN 60034-30-01. Initially the standard for efficiency was called an EFF standard, but since the EU standard differed from the US standards the IEC decided to make an international standard for electric motor efficiency. This standard provides a list of potential classes for electric motor efficiency as well as the requirement for a motor to be placed in a certain class. The standard grades the motors depending on how many poles they have, from 2, 4, 6, to 8 poles there are different requirements to be in the specific efficiency class. This standard includes motors with output PN from 0.12 kW to 1000 kW and voltage UN from 50 V to 1 kV. This standard provides tables for motors run at different frequencies and shows the efficiency required to be at the efficiency classes. For example, for a motor that has 4 poles to reach IE2 at 50 HZ and 4 kW, the motor would need to be operating at an efficiency of 0.858. By using that table, any motor created can be classified into either IE1 Standard Efficiency, IE2 High Efficiency, IE3 Premium Efficiency, and IE4 Super Premium Efficiency. This standard allows for customers to understand how the electric motor they are buying compares in efficiency to other motors from around the globe.

Impact of IEC/EN 60034-30-01 on design

We are able to use this electric motor efficiency standard to understand the quality of the motors we are buying in terms of efficiency. The efficiency of a motor is especially crucial for our design where we need the motor to provide the most amount of torque for the longest time possible to aid the line workers for the entirety of their job. When we are buying motors, we are able to reference this standard to compare the efficiency of the motor to the chart to understand its quality compared to other motors.

IEC/FDIS 80601-2-78 Medical Electrical Equipment Basic Safety

The IEC/FDIS 80601-2-78 discusses the safety and performance of medical robots that interact with patients. Specifically, this standard is discussing the use of robotics that aids in: rehabilitation, alleviation, assessment, or compensation.

Impact of IEC/FDIS 80601-2-78 on Design

The IEC/FDIS 80601-2-78 is important to consider while we are designing our exoskeleton. Although our exoskeleton isn’t specifically used in the medical field it is important to understand what standards would be in place if our project was active in a medical field. By considering those constraints, we can ensure if any line workers that could be using the exoskeleton who already have joint issues will still have access to using our exoskeleton.

JWG9 Medical Electrical Equipment using Robotic Technology

JWG9 is literature that is meant to prepare international standards and other publications concerning the common aspects of the design, development, and installation of medical equipment, software, and systems. While our lower limb exoskeleton is not necessarily a medical device it is still an electronic device that is directly attached to the body. Furthermore JWG9 is a part of the ISO Technical Committee 299. For this reason, JWG9 will have direct impacts on our design and implementation. There are numerous safety standards that we must adhere to to mitigate injury and unexpected consequences.

The Joint Working Group 9 (JWG9), formally created in 2011 to specifically focus on collateral like safety standards for medical electrical equipment. This JWG9 brought together mechanical machinery experts and medical electrical equipment experts alike. They all agreed that a “degree of autonomy” is what set apart medical electrical equipment and a medical robot. They came up with a list of requirements and standards that will impact the design, instruction, and operation of medical robots. This will overlap with our device as the lower limb exoskeleton is definitely considered a robot with its degree of autonomy in the software. The part where we stray from “medical robot” is that there is no real medical operation that the exoskeleton will be performing. However, our design will be using standards that can be found from the work of JWG9 because we are looking to maximize safety.

Impact of JWG9 on Design

Joint Working Group 9 has agreed on a list of standards that must be applied to all medical robots. Our lower limb exoskeleton will be considered a SD Shared Decision” device. Meaning both the exoskeleton and the user will be present in deciding on the function and movement of the device. The monitoring will be conducted by both humans and computers. Generating, dependent on both human and computer. Executing is also done by both humans and computers. Finally, the selection is done solely by the human. This means the human decides on the movements of his/her legs, as well as the movement of the device. However, all other functions of the device are shared with the human, as they work in conjunction to complete a task.

JWG9 states that because of the device being a SD unit, there must be particular measures put in place, in order to ensure safety of the user. This includes, user based, emergency stops. Mechanical stops, as well as limiting the device's autonomy. JWG9 will meet again as time goes on and more research has been done on medical robots and exoskeletons.

ISO 13482 Robot Safety for Personal Care Robotics

International Organization for Standardization (ISO) 13482 is a standard for robots and robotic devices, specifically safety requirements for personal care robots. This is one of the most important standards of this section, as it pertains directly to the safety of the device. This standard specifies guidelines and requirements for an inherently safe design as well as protective measures and the information on use of personal care robots. This standard is specifically written for the classification of the following three robots: mobile servant robot, physical assistant robot, and a person carrier robot. While our lower limb exoskeleton is not a mobile servant robot, it can be debated whether or not the exoskeleton is a person carrier robot. The device is, without a doubt, a physical assistant robot. The reason being, our device will be assisting the movement of a lineman, pole climber. It will be working in conjunction with the climber to push and assist the climber reach their goal of climbing to the top. The standard states that these types of robots are typically performing tasks that improve the quality of life of the intended users.

ISO 13482 describes hazards that these types of robots can be associated with and proposes requirements that mitigate or otherwise eliminate the risks associated with these hazards. Not only does it provide a blanket requirement for all personal care robots, but it also delves into each personal care robot type. Following these requirements will surely mitigate and eliminate all electrical and mechanical risks associated with the lower limb exoskeleton. This will ensure the users safety, which is a key value for FPL and our team.

Impact of ISO 13482 on Design

ISO 13482 is the safety requirements for personal care robots. These requirements are there for devices such as our lower limb exoskeleton. The exoskeleton being considered a “physical assistant robot”. This ISO will keep our design accountable for the safety and wellbeing of the person. These requirements are a set of standards that the design must adhere to in order to keep the user safe. The ISO 13482 has been developed by keeping inexperienced users in mind. It has been written so that even a user who is unfamiliar with the device, can operate it in a safe manner. This is incredibly important because these lower limb exoskeletons are going to be used by many new people on a regular basis. ISO 13482 has requirements such as: emergency stops, protective stops, limits to work space, speed control, force control, collision avoidance, and stability control Not all of these apply to our exoskeleton design, as there is no artificial intelligence moving the person. The most important requirements that must be put in place are emergency and protective stops, as well as force control.

F48.91 Terminology for Exoskeletons and Exosuits

The F48.91 discusses the terminology used for exoskeletons and how they should be classified when talking about personal protective equipment. Due to exoskeletons being wearable, this F48.91 standard seeks to add a standard of terminology and specific certifications for exoskeletons to make consumers and businesses understand their use and capabilities more. This standard creates a classification for exoskeletons with clear definitions. The first being a medical exoskeleton. The medical exoskeleton encompasses any exoskeleton designed for an amputee, injured patients, or the physically disabled. The second category consists of industrial exoskeletons. This category of exoskeletons is defined as an exoskeleton that is used by an employee who is working in a warehouse, factory, or logistic setting.

Those exoskeletons would be those who are used for carrying loads, enhancing mobility, increasing joint support, and allowing for workers to have a longer duration of working without fatigue. The third classification of exoskeletons is military exoskeletons. That classification is used for any exoskeleton that is used by the military and aids in a soldier's effort to march further, carry heavy weaponry, or another task to aid in a soldier's duty. The fourth exoskeleton type is a public safety exoskeleton. That type of exoskeleton is used for first responders who require additional force to move heavy objects while searching for victims in a compromised site. The last classification is the recreational exoskeleton. That type of exoskeleton is for personal use for things like sports, working on personal matters such as home or yard work, or anything else that would require an exoskeleton.

Impact of F48.91 on Design

The impact the F48.91 has on our design is that it allows us to understand where our market is and what types of markets are available for exoskeletons. Our exoskeleton falls under the industrial type of exoskeleton. That standard allows us to design under a specific guideline and classification. In addition to understanding the classification, we are able to ensure we are labeling our design in the proper way to ensure it is only used for those means. In this case, labeling our exoskeleton as an industrial exoskeleton will ensure its intended use of aiding with climbing is not mistaken for a recreational or even a medical exoskeleton.

F3358-18 Labeling and Information

F3358-18 is a standard practice for labeling and information for exoskeletons. There are various requirements and recommendations from this standard that will have a direct impact upon the design of our lower limb exoskeleton. For measurements F3358-18 states that everything must be in SI units as the universal standard. It is stated however that this standard does not account for the safety concerns, if any, associated with its use.

The purpose of F3358-18 for labeling is to make it an international standard so that anyone can easily read and understand the capabilities and warnings of the device. This is especially important for our exoskeleton because we do not know who the end user will be of our product. We want to make the user experience as enjoyable and easy as possible. This has to do with safety as well as ease of use.

Impact of F3358-18 on Design

F3358-18 has profound implications on our design that result in huge shifts in the way we did build and design the frame as well as the electronic components. The fact that labels are a necessity means we must know all exact values (dimensions, measurements, ratings, etc.) of every single functioning component of the lower limb exoskeleton. Furthermore, each of these values must also be converted to SI units so that the labeling falls into code for the F3358-18 standard.

This will also impact the layout of our cabling as well as where each component is located. The reason being, the labels must be apparent and visible. We must ensure all parties who are using the device and wish to know anything they want about its properties can be found right in front of them. This will ensure each label is located in the correct location so that it is adhering to the standard F3358-18.

F48.01 Exoskeleton Design and Manufacturing

The F48.01 standard discusses the design of the exoskeleton with a particular focus on the functional components. This standard ensures that the structural integrity of the design is at an adequate level to prevent failure and potential harm to a user of the exoskeleton. This standard also discusses the electrical components such as the embedded components and energy system to have an understanding of what the maximum and minimum requirements are to run certain types of exoskeletons. The cooling aspects are also considered in this standard. To ensure that no components produce too much heat that they would harm the user, the cooling systems are required to be at a specific range of degrees. The software is also mentioned in these standards to ensure that there are enough safety measures taken in the software side if there is an electronic failure, the software can notice it and activate a failsafe.

Impact of F48.01 on Design

Understanding the standards in the F48.01 is crucial for our design to meet the needs of both electronic and mechanical components to ensure the user is as safe as possible. Due to the nature of exoskeletons and how integrated they are with the user's body, it is imperative to have each component as safe as possible to avoid injury. These standards also give our team an understanding of what most exoskeletons are providing when it comes to structure, electrical supplies, and cooling so we can ensure we are providing an adequate amount of each component.

F48.02 Exoskeleton Human Factors and Ergonomics

The F48.02 standard follows the electrical and mechanical aspects standards and discusses the human aspect of designing an exoskeleton. This standard focuses on user-centered design of an exoskeleton for each type of exoskeleton. For a team designing an exoskeleton for medical rehabilitation, the exoskeleton would need to accommodate the ergonomics of the user to ensure the most optimal aid to the patient. For industrial and military exoskeletons, there are standards for the ergonomics of the exoskeleton that focus more on safety due to the exoskeleton providing more force to aid with heavy loads.

Impact of F48.02 on Design

The F48.02 standard is important to consider for our design process due to how it ensures our exoskeleton will be accessible to more people with different ergonomic needs. Since our design is an industrial exoskeleton it would need to have ergonomics that focus on safety and comfortability when moving heavy loads for a long time. Specifically in our design, we are integrating a system in the joints to extend or contract the femur and calve rods to accommodate for people with differing height and calf to femur ratios.

F48.03 Exoskeleton Load Handling and Environmental Considerations

The subcommittee that created the F48.03 has targeted the environmental impact of creating exoskeletons to ensure each exoskeleton meets the required standard to minimize the impact of the environment on the exoskeleton. For industrial and medical exoskeletons it is crucial to consider how things like heat, rain, wind, and other environmental hazards will affect the exoskeleton. This standard provides the information to create an exoskeleton robust enough to withstand those environmental hazards. This standard shows the required testing needed to ensure the finished product can hold up to the required environmental strain during use.

Impact of F48.03 on Design

Since our design is going to be used in an outdoor environment, it is crucial to meet the standards listed in the F48.03. Especially since this design will be used in Florida, where the environmental hazards are higher than other states. This standard allows us to know how to test to ensure our design can hold up in the elements and not malfunction or deteriorate due to humidity, rain, heat, or any other environmental hazard.

F48.04 Exoskeleton Maintenance and Disposal

The F48.04 standard discusses the required steps to dispose of an exoskeleton to minimize the damage on the environment. The standard also discusses when an exoskeleton is used in an environment that has exposed the exoskeleton to chemicals or a radioactive environment.

Impact of F48.04 on Design

Since our exoskeleton is not going to be around chemicals or radioactive elements, we don’t need to consider that side of this standard. Though we did need to consider how our exoskeleton should be disposed of when its lifecycle comes to an end. This standard will allow us to dispose of it in a way that will minimize its effect on the environment.

Microcontroller Libraries

Microcontrollers are seen in a lot of the things we use every day and seen even more in engineering projects. Since microcontrollers are so common, there have been many types of libraries and documentation created to help standardize their use. Many of the libraries used are open-source and often based in C. This makes it very easy to switch between microcontrollers and easily use the best one for the application. Common microcontroller development boards seen are different types of Arduinos, TI MSP430s, and Raspberry PIs. It is important to understand the standards of using the microcontrollers to use them as efficiently as possible.

Impact of Microcontroller Libraries on Design

The microcontroller is an essential part of the design of the exoskeleton in order to control the motors at the joints. There are many ways to control motors using a variety of microcontrollers. It was important to understand the requirements of the system to choose the correct microcontroller for the exoskeleton. Using the Arduino, we had to use and understand the standard libraries associated with

Arduinos specifically. There are many built-in libraries to help us record our test information, control the motors, distribute power, and many other very useful libraries. Having an understanding of all the resources available to us by using the chosen microcontroller allowed us to make the system as efficient and effective as possible.

Voltage Rating and Standards

The voltage rating and standards given on electrical components are always an important piece of information to know when selecting and testing parts. Voltage ratings can be calculated based on the materials and design of the component, and this information can generally be found in the datasheets or other documentation provided with the component. Common ratings to see are a minimum charging voltage, a nominal constant voltage, and a maximum voltage. Voltage standards are created by organizations such as IEEE defining voltage ranges that are seen in the United States. Most buildings in the United States now provide access to 120 volts and 240 volts at 60 Hz.

Impact of Voltage Rating and Standards on Design

Voltage ratings are important to consider when making electrical designs and matching parts such as matching the batteries to the motors. A variety of motors needed to be tested with equipment that was able to provide a variety of voltages and see a variety of current draws. Once the motor needed was identified, we were able to look at the datasheet to identify the voltage ratings. These numbers are what helped us to identify the required battery for our system. This showed the team how important it is to know how to read the datasheets and identify voltage ratings.

Current Rating and Standards

The current ratings and standards are important to know and understand, and they are generally seen with and in reference to the voltage ratings and standards. Current rating helps the buyer and user understand the expected current draw. The current rating can also indicate the maximum current a system can withstand. This rating is often shown with a minimum, maximum, and nominal amperage. It is also common to see the current with no load and under load, especially with motors. This is told in relation to the speed (in rpm) that the motor can run at with these current draws. Current standards, generally based on which country you are in, are used to standardize the equipment used in residential and commercial buildings. Most buildings have 10 amps in the majority of outlets and 20 amps for larger equipment. There are a variety of standards depending on the industry such as common 30-amp outlets in the defense industry.

Impact of Current Rating and Standards on Design

The current ratings and standards needed to be considered in the design of this project due to the electronics in the system. The current impacts the batteries, control boards, PCBs, and motors. The batteries can have a minimum charging current, a nominal average current, a maximum current, and generally an amp-hour measurement. It was important to know the current draw on the batteries to compare it to the amp-hour measurement.

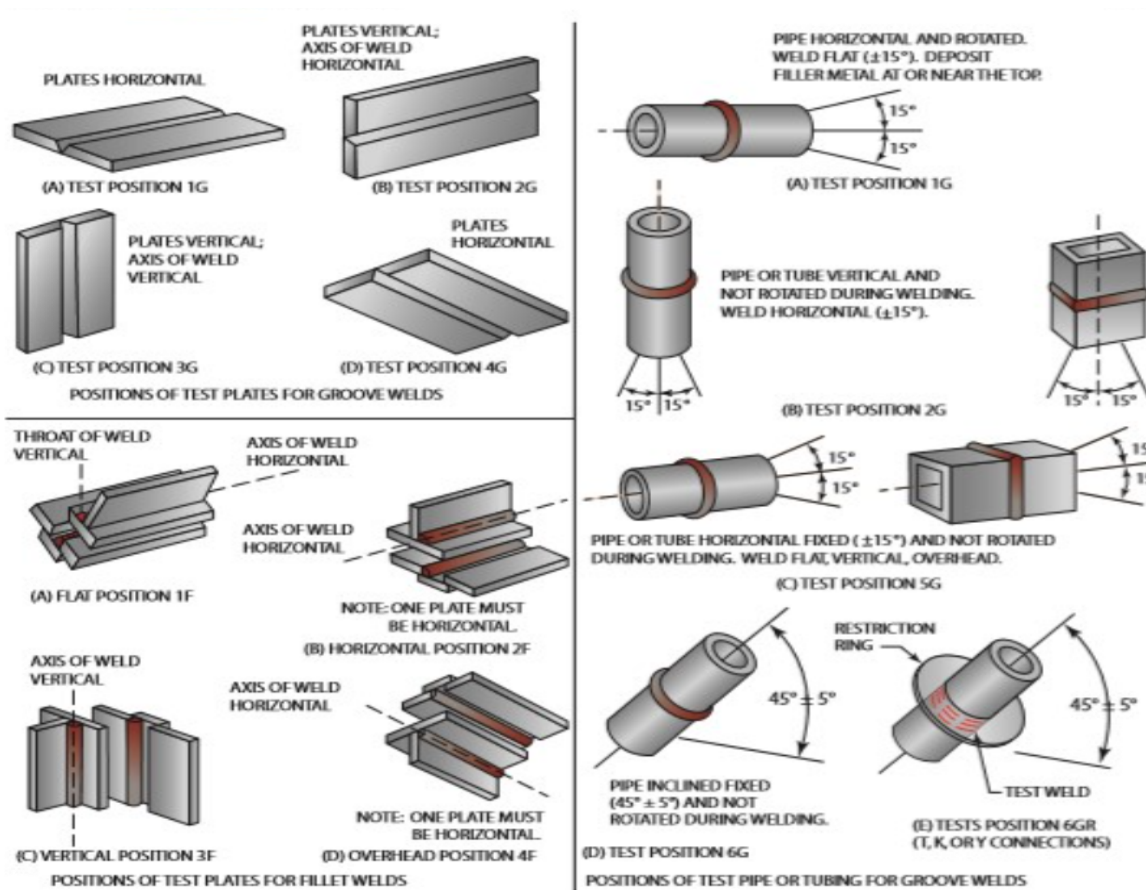
This helps the team understand how long the battery would last in use. The current standards are required to know how the system is going to interface with facility power to charge the batteries. The current rating must be known on the motor control boards and PCBs because the design must be cognizant of the current running through each electrical component. The motors also have motor ratings that help us to know how much current the motor can handle and what speeds the motor will see. These measurements are important calculations in the exoskeleton design.

Metal

There are many different ways to bond metal together with the most common being welding. The most common standard is known as the PQR (Procedure Qualification Record.) It contains a variety of test welds performed and properly tested to ensure that the weld created, will be a proper weld that won't break easily. This is a common practice to follow as it will ensure that the welds are being done properly and safely.

The figure below shows various welding positions that are used. Some of these welding positions will be used for this exoskeleton project, so understanding these techniques is necessary to complete the exoskeleton building process correctly.

Figure 4.1.1 Types of welding positions



Another standard is the actual metal itself. A few of the characteristics are hardness, compressive and tensile strength, corrosion resistance, ductility, toughness, and strength. These are all important when choosing a metal or during its creation to ensure that the proper metal is being selected for its appropriate application. Mechanical property testing is a type of property testing to measure certain qualities of the metal such as strength and ductility. Another type of test is a salt spray test, which is widely used to evaluate how strong its corrosion resistance is.

Impact of Metal on Design

The choice of metal plays a major impact on the overall build of the exoskeleton. If it is too heavy, the weight will be too much for the user. If it is too light, then the exoskeleton could be too fragile and light to help the user ascend or descend. After researching various types of metals and the best option for our needs, we decided to use 6061 aluminum. This type of aluminum is a precipitation-hardened aluminum alloy that contains magnesium and silicon.

It is almost as strong as steel but has the ability to be more flexible under the impact, which is exactly what linemen must be able to face while climbing utility poles. If we used regular aluminum (most common being 3003.) It would not be able to withstand the day-to-day operations. It is used mainly for general-purpose moderate-strength applications. If we decided to proceed with steel instead, the steel would be stronger than aluminum, but it would weigh roughly two-thirds more. The entire exoskeleton will practically be made from metal so it is vital that we can make it as light as possible but at the same time, make it strong enough to work properly. If steel was used, it would make the exoskeleton less flexible under impact so it can cause some trouble for climbers in various situations.

Batteries

Batteries have standards and regulations regarding most areas of using a battery from materials and transportation to testing and general use. The various standards are RoHS regulation, UL 1642, ANSI/NEMA C18, Thermal protection, and charge/discharge. Batteries can contain dangerous and hazardous materials that require these standards to maintain safe practices in use and transportation. Without proper regulation, batteries can cause damage to either the environment or the people working with the batteries.

RoHS regulation is the main standard regarding the risks of electronic waste to both human and environmental health. This is accomplished through restricting the use of certain materials but also by providing safer alternative material options. Markings indicating RoHS on electronics mean that it uses materials approved by the RoHS regulations. The UL 1642 standard is in place for rechargeable lithium-ion battery regulation. This standard regulates the user's or technician's use and replacement of these batteries. It also helps to mitigate the risk of injury as a result of a fire or explosion from the batteries. ANSI/NEMA C18 is a standard used to regulate lithium batteries, specifically rechargeable and portable. The standard covers the general use of these batteries and outlines any expected misuse of these batteries and how to avoid these issues.

Impact of Batteries on Design

The choice of batteries for the exoskeleton is one of the most important aspects to consider when choosing a design. Make it be one oversized battery, if something was to go wrong, the user is stuck with thirty-plus pounds attached to them which can be very dangerous if they are on top of a utility pole. If we use multiple batteries, we run the risk of not having enough power or a loose connection can cause it to malfunction. If the choice of battery does not have enough voltage, it can cause the exoskeleton to not work and we miss our deadline. If there is too much voltage, it can actually damage the entire system and break the exoskeleton. It is essential to choose wisely and have the battery be one of the last parts chosen because once the rest of the exoskeleton is built, we do know how much voltage the system will need.

3D printing

The current standard for 3D printing is the Y14.46-2022 which has been released by the American Society of Mechanical Engineers. In this Additive Manufacturing standard, the main points to be standardized are the 3D printing material, settings, and printing method. With those standards, there is much room for changes based on design needs as well as evolving technology due to 3D printing being a newer technology. 3D printing has allowed for the production of parts made of many types of plastic or metal in ways that best complement the needs of the product. Some 3D printers specialize in precision but are less efficient on time or material while others are very quick and use minimal material but lack the precision of other options.

Most 3D printing uses material extrusion where the material is pushed through an extruding nozzle and is heated to a malleable state at the time of extrusion. The extruder is then moved back and forth around a build plate to build a layer of the design. Once the layer is completed the build plate is lowered or the extruder is elevated to move on to the next layer. Another 3D printing style is binder jetting. Binder jetting is used by having a thin layer of metal, sand, or ceramics that can be solidified using a binding agent. There will then be a nozzle that excretes the binding agent on the build plate and solidifies the powder based on the design inputted. The build plate moves down and more powder is applied to create the next layer until the design is complete.

Impact of 3D printing on Design

3D printing has been a crucial part of prototyping our exoskeleton. We are able to use 3D printing to test if any mechanical design will fundamentally work before creating it in metal. With those 3D printed prototypes greatly lessen the cost of prototyping in comparison to needing to manufacture the design in metal prematurely. With 3D printing, we are able to test how parts like the motors, bungies, sensors, etc. would work on the exoskeleton prior to the manufacturing phase. Another way we did be able to use 3D printing is in construction motor test benches to test the capabilities and gear ratios of motors.

IEEE 1394

The IEEE 1394 is an important topic when it comes to real-time data transfer. Using the IEEE 1394 standard, which is an interface standard for high-speed communications for a serial bus. This form of data transfer can be used for software updates and for various other applications seen fit for this application of the exoskeleton. It was designed in 1986 and produced by Apple in 1994. The bit rates vary from 400-3200 Mbit/s or in a more common size, 50-400 MB/s (megabytes per second). For the current, the max Amps is 1.5A while the max voltage is 30V. With these speeds and max powers, it can easily handle any software upload or download needed.

Impact of IEEE 1394 on Design

The IEEE 1394 real-time data transfer has a strong impact on every electrical part of the exoskeleton. The software that is transferred to the exoskeleton will be how the parts such as the motors interact. The motors can have various speed outputs and directions so the importance of the code that is being transferred in by the IEEE 1394 real-time data transfer is crucial. Another impact is that the data speed transfer is "instantaneous.” The team can constantly try various different codes and if it needs to be, alter or debug any code we choose to our liking.

IEC 60130-10

The IEC 60130-10 standard is an important consideration when designing the power distribution and control of your system. IEC 60130-10 sets standards for low-frequency and low-voltage DC connectors. These connectors are essential in any designs that require the system to be powered or charged using an external power source at a low voltage. The standard covers connectors that range up to 3MHz and 34 volts.

Impact of IEC 60130-10 on Design

The impact the IEC 60130-10 has on the exoskeleton is simple, it is what will connect the power distribution system and the controls. It is very important that we understand how it works and be able to properly be able to connect the important various parts so that the linemen will be able to use an exoskeleton that actually works and be beneficial to them.

ESD Protection

There are standards that outline protection against electrostatic discharge (ESD) that are common in all industries using ESD-sensitive devices. The majority of electronic components such as circuit card assemblies are ESD sensitive and require grounding of the workstation and the person working on the device. Without proper grounding, ESD can pass through the worker which can result in serious injury or worse. ESD grounding can be accomplished through different types of straps such as wrist straps to the workstation. The workstation can be grounded to a large chassis, or it is common indoors to see workstations grounded straight to the outlets. ESD standards are generally seen in military standards such as MIL-STD-1686C which outlines ESD sensitivity and testing standards, as well as ANSI standards such as ANSI/ESD S20.20-2021 which is designed to replace the previously mentioned standard.

Impact of ESD Protection on Design

ESD standards on sensitivity, testing, and protection are important to the design of this exoskeleton for many reasons. The electrical design contains multiple components that are ESD sensitive and need to be treated as such when being tested, installed, or otherwise handled. It is also vital to be in consideration due to the work environment where the exoskeleton will be used. The workers will be repairing high-voltage lines which greatly increases the risk of coming in contact with electricity and electrostatic discharge. The design needed to be conscious of how the system would handle ESD exposure and protect the user. The frame and all metal components require proper finishing or filming, and it is imperative to properly ground these components. ESD is the same as any other electricity in the sense that it will take the path of least resistance and has a natural flow. If the system has a proper grounding, the ESD will discharge through the grounding rather than pass through and possibly injure the user. ESD carrying 1 A or less can be fatal when passing through a user, and the transmission power lines being worked on carry on average 700 A.

4.3 Economic Constraints

Economic constraints are a great and constant concern that must always be in consideration during the production of the prototype. Due to the pandemic, there was a large supply shortage in many different areas that made getting parts for test and build. It was difficult to find the correct parts, but it is also difficult to find parts that can be shipped to the team in a reasonable time frame. During research and part selection, it was important to consider what parts matched the system requirements and would be able to be acquired in time. It is important to run an analysis on the cost versus functionality to determine the price point each component can be purchased to effectively use the budget. The idea behind this project is to replace the competitor's current exoskeleton design that is available to Florida Power and Light. The design, parts, and price need to be done in such a way that these exoskeletons will eventually be able to be repeatedly built on site by FP&L. The competing price point of the other exoskeleton is $5,000. This project needs to be able to be built for a considerably less amount for it to be considered by FP&L to use.

4.4 Time Constraints

The time constraints of this project stem from a large variety of areas. It is important for every member of this team to meet their deadlines. This project has an added element of difficulty because our team is working conjointly with a team of mechanical engineering students. It is also very important for the other team to meet their milestones. The mechanical engineering team is also in Senior Design II, so the prototype needs to be in a functioning state by the end of the semester for its showcase. These factors together have given the project a very difficult timeline.

The most difficult and interesting of the team and project time constraints are working conjointly with the Senior Design II Mechanical Engineering team. This interdisciplinary team is difficult because we are at very different stages in the project, to begin with. They had already worked on this project for a semester before we even had a chance to ever know that this existed. There was a lot of information dumped onto us and plenty of catch-up work that needed to be done to understand the project. This has also proved to be difficult because the Mechanical Engineering school has a completely different set of requirements for Senior Design. This means that the two teams have completely different sets of milestones that must be hit for the curriculum to graduate. There were many ideas discussed to make this work, and the results ended up giving the senior design I team slightly more work. This added even more of a time constraint and forced the team to prioritize time management very heavily. There are many moving parts that need to be considered and have to be managed properly to ensure that we can complete this project on time.

4.5 Equipment Constraints

The equipment constraints of this project come from important requirements from the customer. An important constraint of our equipment is that the exoskeleton and user must be less than 131 kg in total. The weight requirements are based on the average weights of each component. The average American male weighs around 86kg, but the number used is one standard deviation higher than the mean in order to create a buffer which is around 110 kg. The expected weight of the tools being carried by the worker is 7 kg. This does not leave a lot of weight because the target user is generally a large, adult male and because the exoskeleton is aluminum. There is approximately 14 kg in allowance for the exoskeleton itself. This requires a design that minimizes excess material.

Another important constraint that is coming from our customer and the nature of the project is the tools that must come on the exoskeleton. The exoskeleton should have room for the linemen to have a tool belt containing tools needed for the job. Tools like hammers,crimping tools, wire striping tools, bolt cutters, screwdrivers, wrenches, etc. are needed for lineman to be able to provide maintenance to the power line once they have ascended the pole.

Another aspect of equipment constraints is the availability of machinery for manufacturing, testing, or software developing. For our initial testing we are utilizing the Innovation Lab at UCF to manufacture the motor test bench. We are limited by the type of drill presses they have as well as ensuring we can have a time slot to be there. We also need to consider the constraints of the people working at the Innovation Lab. There are many other groups doing projects at the same time that are fighting for the advice, supervision, or other needs from the people running the Innovation Lab. We did also require testing equipment to test torque, current draw, and other variables required for calibrating the motors on the exoskeleton. That equipment is either an added cost if we need to purchase it or we must consider the availability and time frame if we are utilizing UCF's resources.

4.6 Health and Safety Constraints

There are many health and safety constraints in this project, as well as the work environment the exoskeleton is expected to be used. An exoskeleton brings risks because there will be powered motors attached to a person's joints. There are a number of concerns with a part of the body as easy to injure as a joint. The work environment, climbing and repairing power lines, poses many constraints. There are a range of constraints and risks such as the high voltage lines, climbing the high poles, and all other concerns already associated with this type of work. There are also health concerns and constraints that are often seen in power line pole climbers. These health concerns include musculoskeletal ailments that are common from this field's required physical exertion.

The exoskeleton is designed to reduce the health concerns of the job, but, if the design is not done correctly, the system can make matters worse. It is important to do incremental testing to verify the safety of the components and the setup being used before ever touching a person. There are also health and safety concerns anytime components such as motors and batteries are used. These components have potential issues when in use such as overheating or explosion. Following regulations that are in place and using safe and proper testing procedures can reduce this risk. However, this alone is not enough. The system must be designed using cooling systems to stop the components from ever overheating. Proper regulations and testing procedures will help reduce and mitigate health and safety risks.

4.7 Environmental Constraints

There are many environmental constraints because the system is designed to be used outdoors in a dangerous environment. The system is exposed to the outdoor elements, meaning things such as wind, rain, heat, humidity, and lightning all need to be considered with the exoskeleton. There are requirements to simulate this that come from the customer. These requirements cover the use of the system in extreme temperatures as well as when being exposed to water. The exoskeleton is going to be used to work on power lines. This means there are a number of high risks for the user of the system such as falling, high winds, and thunderstorms. The system must be secure and safe to mitigate these risks. If there is an incoming storm, the worker needs to be able to safely stop working and leave the area without putting themselves or the rest of their team at any more risk.

Beyond considering the environment acting upon our exoskeleton, it is also important to consider how our exoskeleton can impact the environment. Using lithium ion batteries, our team must ensure our design allows for and encourages the proper disposal of lithium ion batteries to ensure they are able to be recycled. Due to the limited accessibility of lithium and the environmental damage excess mining for lithium causes, it is crucial that our design accommodates and encourages each battery to be recycled. We did also use many other electronic components that still need to be recycled, although not using an as limited material like lithium. Components like the motors, wires, sensors, and the frame of the exoskeleton require proper recycling to reduce the impact on the environment in landfills.

4.8 Manufacturability Constraints

The manufacturability constraints are important to constantly consider in a large project with strong electrical components such as the motors. They are important to think about in both the research and development of the project as well as the later production of the design. The exoskeleton having expensive parts is an important constraint because it greatly limits the parts you are able to procure and limits the functionality and output of the system. The team had a goal of

$5,000 to produce a single exoskeleton to meet our sponsor's requirements, but we have researched parts that would push the budget well past its limits. It was important to be mindful of these constraints in our research and testing to stay under our goal budget. There are also many constraints in testing with 3D printing and development and building with metal cutting and working. There are a variety of design constraints and standards as well as manufacturing constraints and standards that need to be considered.

Another manufacturing constraint is the time that it takes to create custom parts. There is no exoskeleton available to purchase, so everything has to be created from scratch. From the correct sizing of the metal to fabrication, to sometimes even the motors that we did use. There is a wait time for creation and delivery. The global pandemic of the virus Covid-19 has caused massive delays in the custom fabrications scene and the overall processing times of certain items so being flexible with the materials that we can use and being able to do certain things such as welding in-house, can determine if we did have the exoskeleton completely finished before our deadline.

4.9 Ethical Constraints

There are a number of ethical constraints and concerns when it comes to the design and use of the exoskeleton. Safety is an ethical concern in all engineering projects, and our project gives extra constraints due to its nature. There is an ethical concern about the system design possibly making the job more dangerous than previously imagined. The exoskeleton must be properly tested and the quality of the design and build must be assured before any person is going to be attached to the exoskeleton. There are also ethical concerns anytime a system is using metal, electronics, batteries, and any other materials and components that could be toxic or environmentally unfriendly. These ethical constraints impacted our part selection and research.

4.10 Sustainability Constraints

Sustainability constraints for this project are very important to be cautious of the system's expected use outdoors. The outdoor use of the exoskeleton poses many risks in Florida's harsh environment. There is always a risk of inclement weather, especially during hurricane season, and the expected daily weather is harsh in its own aspects. This environment means the exoskeleton could experience damage or part loss which gives sustainability constraints. The design should be able to withstand the environment, but, in the worst case, the part selection should minimize risk to the environment. Part selection is focused on finding parts that will work effectively and withstand being used outdoors. The design is focused on making sure those parts stay together on the assembly throughout rigorous use.

Another sustainability constraint is the ability to use materials that are easily replaceable. There are hundreds of different parts and practices that we can do to have this project built, but we need to ensure that the parts that we are using aren't going to impact the necessity in the case that a part needs to be replaced. It is crucial that for example, if a motor needs to be replaced, it is not a special custom-made one that will cause the company to wait a long period of time for it to be made and delivered. It is also important that whatever parts we do use, the less carbon footprint created, the better it will be for future generations to come.

4.11 Social and Political Constraints

There are social and political constraints associated with any engineering project that relates to a field a team has limited knowledge in. This requires communication with experts in the field that the system is being designed for. For our team and design, the exoskeleton is planned to be used in the energy industry for the company Florida Power and Light (FP&L). We needed to maintain constant contact with FP&L to both answer and ask questions and give updates of the design of the exoskeleton. This was accomplished by doing weekly meetings with our person of contact at FP&L and maintained contact through email. The Mechanical Engineering team also met with actual workers who are expected to use the exoskeleton in the field to learn how the job is currently being done and the safety measures in place.

This happened before our team joined the project, but we were able to watch the many videos taken during these meetings. Speaking directly with the sponsor and the workers who will use the system helps us to build the most effective system but, more importantly, the safest. Another political constraint is to make sure that we are not stealing or “copying” other competitors that are in the same market due to various legal issues. As discussed earlier, there are various competitors creating an exoskeleton. They all have various designs and codes that are protected and we need to make sure we are not crossing any boundaries as there would be legal disputes if we accidentally do.

4.12 Ergonomic Constraints

FPL requires that the lower limb exoskeleton be an ergonomic, easy to use device that assists the climbers without a steep learning curve. It is important that the design improves ergonomics, because of the amount of stress that the climber experiences on his or her body. Climbing a power pole is an extremely strenuous task that requires the user to put all of their weight on their two feet, which are attached to a pole. This leaves the users back and legs in a vulnerable position, without the proper form and technique. This amount of stress on these body parts can and will eventually cause long term injuries, taking the worker out of commission and lowering their quality of life.

For these reasons, it is imperative that our lower limb exoskeleton improves overall ergonomics during the climb. To ensure proper ergonomic movement of the legs the range of motion of the legs will be free, but assisted. This enables the user to move their legs however they would normally to complete the task. However, the forces needed to push their body up with their legs will be assisted and require less force from the user. Furthermore, there will be a stop going both ways to ensure the user does not hyperextend or overly bend their knees or hips. To improve the posture of the user, a back rest will be implemented. This is to prevent health complications of the back and keep the user in the proper position.

Ergonomics are a very important constraint as the user's health and safety is of utmost importance. Our entire device has been specifically designed to improve and maintain natural ergonomics while under operation. As it must be comfortable and easy to use to improve the users day to day.

4.13 Weight Constraints

Another important constraint that FPL is limiting us to is the weight limit of the device. The lower limb exoskeleton is meant to assist the user and not weigh them down. Any added weight will be over cumbersome and awkward for the user. Keeping this in mind, our exoskeleton can not be weightless as it must be powered and provide structural support. Keeping this in mind it is important to remember that the exoskeleton will be generating force of its own. So the weight of the device must be less than that of the force it is generating. To do so the frame will be constructed with the light material of Aluminum Alloy 6061, as well as being hollow. This is a huge constraint as the weight of the lower limb exoskeleton has a direct impact on the climber and their abilities to do their job. FPL says that the device must weigh no more than 13.6 Kilograms.

4.13 User Constraints

It is a requirement of FPL that the exoskeleton be adjustable to accommodate users of all sizes. This is a constraint that on the mechanical side requires additional components to the frame. On each of the joints there will be a pin to adjust the length of the rod going into the joint. That will allow people of varying height and femur to tibia ratio to have access to utilizing our lower body exoskeleton. On the electrical side, we have ways we can consider the users height and weight to determine the parameters imputed into the motors. We can use some sort of interface to allow the user to input their height and weight into the exoskeleton's software. With that data, the software can run it through an algorithm we create to provide more or less current to the motor to prevent the motor from being too strong or not strong enough for specific users.

By the end of senior design 2, the constraints have not changed.

5 Administrative Content

This section outlines all financial aspects of the exoskeleton and the timeline that we follow in order to complete the project and be successful.

5.1 Project Budget

To create an exoskeleton that will help linemen be able to climb poles more efficiently and for it to be less strenuous on the body. It will consist of multiple motors to help linemen ascend and descend high-powered electrical poles. It needs to be cheaper than the other exoskeletons on the market.

There are many vital factors that are involved when it comes to the budget. The first one is the actual exoskeleton frame itself. Before production of the prototype, we anticipated the total cost of the frame which includes the 6061 metal, to cost around $450. After numerous quotes from fabrication shops, the official amount we did spend on the frame will be $600. The actual machining part will be done “in-house” at the University of Central Florida. By taking advantage of the shop we have here at our university, the additional cost will be cut down to $0. The $600 will be for all materials and some of the labor.

Now, moving forward to the part selection that will be in the exoskeleton, firstly what we would need are the motors. One of the most challenging parts when building the exoskeleton is figuring out which motor will best be able to help the user most efficiently climb a utility pole. Finding a motor that can produce a strong enough force of at least 10-15 Nm (Newton-Meters) minimum but also be low enough voltage to minimize the usage of the batteries is crucial. After initial research and seeing various costs online, we had a strong estimate of $700 a motor. The exoskeleton will be using four different motors, one on each knee, and one on each side of the waist. The total estimated cost comes in at $2,800. We have access to a lab at the University of Central Florida in which one of the managers there has multiple different motors that we can test. After a couple of “testing sessions,” we are still pinpointing exactly which motor we did acquire for this build.

The next major component of the exoskeleton is the batteries. During the initial discussion, we were deciding if it would be best to have one large battery or if we should do multiple smaller ones. After further review, it was best decided that multiple smaller ones are more ideal than one singular one. This was decided due to the fact that if on
e of the batteries “dies,” there would be other batteries that will continue to allow the exoskeleton to function properly. We found over five different potential batteries that would be able to power the motors and everything else that is needed.

The table below shows all of the major components as well as the expected price per unit, the actual cost per unit, and the total cost of each component that was procured for the project.

Table 5.1.1 Project Budget

Project Budget			
Item	**Anticipated Price**	**Purchase Price**	**Total Cost**
Exoskeleton Frame	$450	$600	$600
Motors	$2,800 (four units)	$232 (four units)	$832
Batteries	$693	$ TBD	$ TBD
Wiring	$35	$ TBD	$ TBD
Control Board	$25	$ TBD	$ TBD
Motor Speed Controller	$10	$116.99	$948.99
Motor High Torque Speed Reduction	$14	$ TBD	$ TBD
High Power Motor Driver Module	$11	$20.09	$968.08
Miscellaneous	$350	$29.90	$995.98
Total	$4,352.89		$995.98

We took the mean price amount as our cost. Roughly every battery would be about $173.22. We need four of them, so the estimated cost would be $692.89. Once we figured out which motors we needed, it became quite clear which motor we would use. As discussed earlier, we are still in the testing phase and have not decided on a battery just yet. Once we figure out the rest of the components, then we should have a strong idea of which one to buy.

Another thing that we need to consider is the control board, we need a board that is capable of controlling all the motors and allowing user inputs. After searching online, we estimated the total cost to be roughly $25. The control board is still being discussed as well and will be chosen at the earliest convenience.

Other various things that we need are specifically for the motors. We need a speed controller, speed reduction, and the module to make it work properly. The total estimated cost for all three parts online is roughly around $35. The final cost for the three parts at the time of purchase still has not been confirmed but should be roughly the same $35 estimated price point. We had an initial budget of $350 for miscellaneous parts and things and should still be able to fall within that price point.

Part	Price
Exoskeleton Frame	$163
Motors	$127
Batteries	$84
Pulley	$39
Control System/Peripherals	$352
Wiring and Assembly Parts	$162
Test Bench Set up	$0
Total Cost	$927

In senior design 2, Our Final cost came out to $927. Slightly more expensive than expected from senior design 1 with slight change of costs. As seen above, we have had enormous support from the innovation lab and we were able to choose components that fit below the budget and we were able to save on many costs along the way.

5.2 Milestones

The table below shows all of our important project milestones and the date we started, planned end date, and the official deadlines that it needs to be completed by.

Table 5.2.1 Project Milestone Documentation

Project Milestone Documentation			
Milestone	**Start Date**	**Planned End Date**	**Required End Date**
Divide and Conquer	09/02/2022	09/12/2022	09/16/2022
Divide and Conquer V2	09/19/2022	10/04/2022	10/07/2022
75 Page draft	10/10/2022	11/02/2022	11/04/2022
125 Page draft	11/07/2022	11/14/2022	11/18/2022
Final Report	11/21/2022	12/05/2022	12/06/2022

To create an exoskeleton that will help linemen be able to climb poles more efficiently and for it to be less strenuous on the body. It will consist of multiple motors to help linemen ascend and descend high-powered electrical poles. It needs to be cheaper than the other exoskeletons on the market.

The milestones we have been assigned by our Senior Design 1 class are laid out in table 5.2.1 titled “Project Milestone Documentation” and give us a timeline for when we are required to have our report written. We did first begin with our initial document titled “divide and conquer.” The purpose of this first document is to lay out the general overview of the project that we have chosen and other various requirements. For example, it will need to be 10 pages and include some of the following, the project description which states what we were doing and trying to achieve, a statement of motivation and why we want to take on this challenge. We also need a list of requirement specifications. This is a list provided by our sponsor, Florida Power, and Light. There are various things the sponsor would like to see such as safety requirements and the strength of the exoskeleton, this is the most important as we have the user's safety first in our minds.

Another requirement is a block diagram, we need to be able to show how we did everything connected together and who will be in charge of doing what. For example, Kaden will be in charge of the battery and how it will connect to the power distribution PCB. This is important to keep all team members accountable and also allow everyone to have a leadership position when it comes to a certain section of this project. The final major component of the divide and conquer assignment is the estimated project budget and financing. It is important to have at least a rough idea from the very beginning so that you know exactly what you are getting yourself into. Our sponsor has given us a budget of $5,000, so it is important that we can stay within this price point, it would be even better if we can go well below. This assignment Divide and Conquer is due on September 16, 2022. We began this assignment on the 2nd of September and had it planned to be finished by the 12th of September.

The next assignment is a revamped divide and conquer “V2.” In this assignment, we take what we have done in the first version and make it more “professional” and also this time, add a house of quality analysis. A HOQ (house of quality analysis) takes the customer's requirements and desires and places them on a table. In this table, every single requirement is then decided with certain symbols on how strong it needs to be, or if it is of less importance. The rest that the updated divide and conquer needs is labeling. There are strict guidelines on how each table, and figure must be labeled and its formatting. For example, all tables and figures must have a title, and all tables and figures can not be split into two pages. The last labeling is that for every engineering specification, it must be verifiable and we must be using real numbers. This updated assignment Divide and Conquer V2 is due on October 7, 2022. We began this assignment on October 19 and we had it finished by the 4th of October.

Now that we finished the initial document, we did now begin the official document that will be submitted by the end of the semester. This next assignment is called the 60-page draft. Since we are a team of five, our actual assignment page count will actually be 75 pages. How to proceed with this assignment is to take what we have already written in the assignment divide and conquer and build on it. We have now also received “guidelines.” Mainly stating paper size, and margin requirements, adding a table of context, appendix, and copyright section. What needs to be completed in this section is the technical content, administrative content, and appendices. There is a list of A-M of content that needs to be added to this paper. Alongside the original Divide and conquer paper that we wrote, we need to begin research and investigate more about exoskeletons and how we did begin the process of choosing parts and how it will work. We did also need a strong design overview, explicit design with a parts list, and plans on how we did build, prototype, and test this exoskeleton. This section also covers our timeline. We need to make sure that everything we are doing will be completed in a timely manner and for us to stay on task with building this exoskeleton. Other than a few acknowledgements and a few other minor things, that is what needs to be submitted for the 75 page draft. This 75 page draft began on the 10th of October and it is required to be submitted by the 4th of November. We had it completed early on the 2nd of November.

The next and almost last milestone is the 125 page submission. This is the same 100 page submission report but since we are a team of five, it is required for us to submit an extra 25 pages. In this section, we already know all guidelines and how the report should be done. So we just continue our focus on research and development of our exoskeleton. As this is happening, we update our budget as well since parts are being ordered and official numbers are starting to arrive. We did also continue communication with Florida Power and Light to make sure that everything we are doing is up to their standards and is being completed properly and in a timely manner. For the 125 page submission report, we began on the 7th of November and will be completed by November 18th. With anticipation that we did have it fully complete by the 14th of November so that we can focus on grammar checking and final touch ups. The last and final milestone that we need to complete is the official final report submission. This is the most important as this will determine our final grade for senior design I. This final submission will consist of roughly 150 pages of our entire research and development of the exoskeleton for the Florida Power and Light Company. This final push will begin on the 21st of November and be submitted by the 6th of December. The deadline is right before the end of the semester, It will all officially be completed by the 5th of December.

The table below is the milestone completion table that we did following for the design, build, prototype, and test for the exoskeleton project for the company Florida Power and Light.

Table 5.2.2 Prototype Milestone Documentation

Prototype Milestone Documentation			
Milestone	**Start Date**	**Planned End Date**	**Required End Date**
Choosing the Motor	09/02/2022	11/02/2022	11/14/2022
Choosing the Battery	09/02/2022	11/02/2022	11/14/2022
Choosing the Microcontroller	09/02/2022	11/02/2022	11/14/2022
Choosing/creating the PCB Prototype	09/02/2022	11/14/2022	11/18/2022
Finish Component Testing (Single battery and motor)	09/02/2022	11/25/2022	11/25/2022
Finish Testing (Single joint of Exoskeleton)	09/02/2022	11/25/2022	11/25/2022
Complete Framing of the 3D Print Prototype	09/02/2022	12/05/2022	12/06/2022

For our next milestone completion, it is all about building the exoskeleton and the overall development. In order to select parts that meet our specified requirements, we have streamlined our selection milestones in table 5.2.2 titled “Prototype Milestone Documentation” to allow each sequential milestone to be reliant on the previous. It first begins with motor selection. We are working with another team that is in senior design II so the overall design of the exoskeleton is complete.

Our job as electrical and computer engineers is to take the design that the other team made, and add electrical components to it so that it can work properly. The first step being the motor, the motor that we need can't be just any off the shelf motor but needs to be strong enough for our minimum requirements. The motor as previously discussed will be based on the force required to move a knee and hip joint successfully to help a lineman be able to ascend and descend a utility pole.

The next important factor is the battery, on our milestone “checklist” we have it being next in line that needs to be chosen. Once we found out which motor we were using, we can now choose a battery that will be capable of powering all four motors. The battery that will be chosen, has to be strong enough to provide power to the motors, microcontroller, and any other parts that require electricity. The size is also another important factor.

We have very limited “real estate” when it comes to placement of our parts so it is imperative that we can find a battery that is small enough but also strong enough to deliver the power needed for the entire exoskeleton. The last part selection that we did need to have is the microcontroller. By having the motor and battery choose, we did need a way to connect everything so that the exoskeleton can work properly. This will be done by a microcontroller. This specific microcontroller will need to be compatible with the motors and be able to control the amount of power the battery will send.

All three of those components will have to be chosen by our chosen deadline of November 14. We have begun researching these components since day one that was the 2nd of September. We chose that specific deadline as it is between the 75-125 page submission deadlines. By then, we did have a strong understanding of how exoskeletons work and the necessary components that we would need to be successful.

The next deadline that is fast approaching would be the PCB prototype that is due four days after the component selection. We have chosen to create a PCB that will control the power distribution of the exoskeleton. During part selection, we have been conducting tests on our electrical components to ensure that the numbers being generated are sufficient enough.

Now that all components, boards have been chosen and purchased, and the exoskeleton frame is built, we can now conduct the actual testing phase of the exoskeleton. Our goal by the end of Senior Design 1 is to be able to test a knee joint using the design from the ME team and the electronic components we were able to compile to work properly and actually be able to assist a lineman be able to ascend and descend a utility pole.

The table below is the milestone documentation that will be conducted and completed in senior design II and is the further development of the exoskeleton.

In senior design 2, we were able to complete all milestones on time and correctly.

Table 5.2.3 Further Prototype Milestone Documentation

Further Prototype Milestone Documentation			
Milestone	**Start Date**	**Planned End Date**	**Required End Date**
Develop the software	TBD- Senior Design 2	TBD- Senior Design 2	TBD- Senior Design 2
Test PCB with subsystem	TBD- Senior Design 2	TBD- Senior Design 2	TBD- Senior Design 2
Full Assembly Built	TBD- Senior Design 2	TBD- Senior Design 2	TBD- Senior Design 2
Full Assembly Test	TBD- Senior Design 2	TBD- Senior Design 2	TBD- Senior Design 2
Final Presentation and Demonstration	TBD- Senior Design 2	TBD- Senior Design 2	TBD- Senior Design 2

As Senior Design 2 begins next semester and continues the project, we already have a milestone documentation guideline that we have in mind in order to continue and continue the project following the necessary timeline. We did shift into creating the software and fine tuning the hardware that will be controlling the exoskeleton. We would also begin further tests on our printable circuit board (PCB), motor control board, and battery control board with our fully built exoskeleton.

The biggest objective for next semester is to have the exoskeleton completely built and to have all components working properly. During the initial build of the exoskeleton, we did troubleshoot any problems that arise. This will be a mammoth of a task due to the number of components and subassemblies being implemented into the next higher assembly, but we are confident in our design, test, and integration abilities to have it done. It is important to thoroughly analyze and test the hardware and software during the build process to ensure an easy integration process into the final build of the current exoskeleton design.

Then finally, to wrap up our project and our time here at the University of Central Florida, we did a demonstration on how the exoskeleton works and submitted any final documentation. This showcase of the exoskeleton build and test will display the current state of the exoskeleton design. All dates are subjective to next semester and the timeframe needed at the time according to milestones and deliverables determined during the next portion of the assignment. These deliverables, milestones, and dates will be driven by the requirements provided according to the Senior Design 2 course.

For senior design 2, we were able to complete all deadlines above except for the PCB requirement. As this is an interdisciplinary team, we were not required to create a PCB for the lower body exoskeleton as we wanted to reduce the amount of risk with this project.

6 User Manual

In this section, we did discuss how to inspect, wear and properly operate the exoskeleton.

Everything discussed in this manual is theoretical and final adjustments may be made once the exoskeleton is fully built. Subject to change if necessary.

6.1 Safety

It is important before putting on the exoskeleton. A full inspection of the suit must be done to ensure everything is connected properly and working correctly. With the skeleton laid down or in a standing position being supported. Inspect all rods, motors, batteries, sensors, straps, and anything else that could possibly be loose or not properly attached to the exoskeleton.

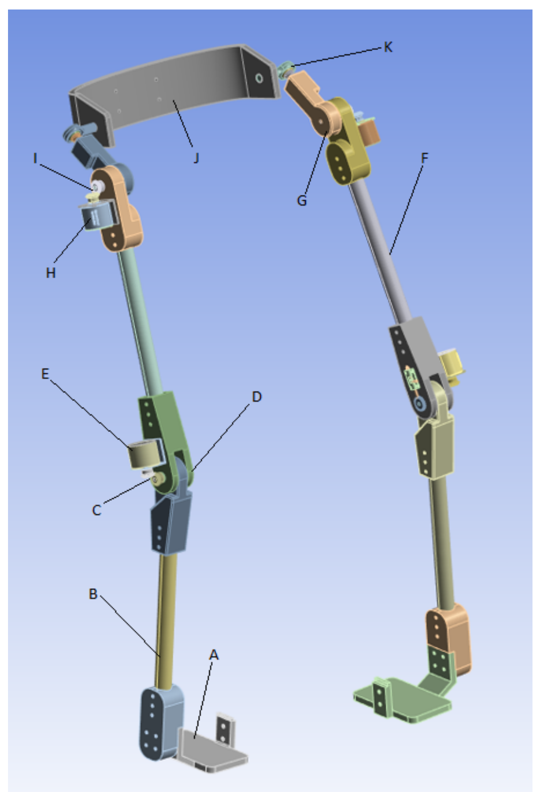


Figure 6.1.1 Theoretical final diagram of how the exoskeleton will look like with every major component labeled to ensure that every part will be inspected before each use.

If there are any metal loose or loose connections, it is imperative to have it repaired before a lineman puts on the suit as this can be a massive safety issue once the exoskeleton is in use. Make sure to check that every bolt, wire, strap, and cable is correctly seated in its right position and is tightened accordingly.

While in operation, if the battery sends an alert that the power is running low. Immediately, or as soon as you can safely do so, begin your descent back down to where you can safely exit the exoskeleton and have it charged. If there are any overheating or loud noises coming from the exoskeleton that is not normal. Have the exoskeleton inspected and Replace any part that might be having trouble.

It is important to always stay alert. This exoskeleton is designed to help a lineman ascend and descend utility poles. It will help relieve the stress that regular climbing can do on the body. But, it is always important to understand that climbing a utility pole is very dangerous. Be very vigilant while you are climbing and when you are resting, try to do an eyeball inspection of the exoskeleton to see if anything is “out of place.” The more awake and aware you are, the less likely something will go wrong. If you are ever unsure of how to operate the equipment, ask your supervisor or the person that is trained for this specific operation.

If the exoskeleton was to run out of power mid-job, it would be important to stay calm. The exoskeleton will still be able to function and move with your body. The only issue is that there is no power to the motors. You will have extra “baggage” on you, but it is important to start descending slowly but confidently. If the weight becomes too much to bear, simply put the exoskeleton in the lock positions to catch your breath and recover stamina. If all else fails and you simply can not move anymore with this exoskeleton now considered “dead weight.” unstrap the exoskeleton in a safe manner and let it fall. Yell down below in case there are any workers that could be hit. This last option is not advisable at all but is a last-case option.

6.2 Startup

The first thing to do after you have properly inspected the exoskeleton is to have it in an upright position, preferably while resting against a wall or support. The wearer will then unbuckle the straps and confirm that the battery is fully charged. If the battery is not fully charged, the user must wait until the batteries are fully charged to take advantage of the suit as long as possible before it depletes. After completing both of these requirements, make sure that the user is wearing the proper clothing underneath. Then you can proceed to “enter” the exoskeleton by laying inside of it.

Once sitting firmly in the exoskeleton. Start buckling the straps from the bottom to top. The first strap is down at the feet. The next strap is at the waist. Once the user is fully strapped into the exoskeleton, there is a switch on the side that will then power on the exoskeleton. Once the exoskeleton is turned on, you are then freely able to move at your leisure and begin working with the exoskeleton attached.

6.3 Operating

Once you have successfully strapped yourself to the exoskeleton and verified that everything is properly working, now it is time to work. At first, it may feel weird moving with the exoskeleton, but with time, you will get used to it. How the exoskeleton operates is as you move, there are sensors that pick up on your direction and to apply force as needed. While operating, you are likely to be walking slower than you usually would but every step is precise. When you approach the utility pole that you will climb, first begin with a few “sample steps.” What this means is to first begin by lifting both knees one at a time for a few times to get a feel for it.

Once you feel comfortable enough, wrap around your main harness strap to the utility pole and strap it onto yourself. The strap that goes around the pole is the “fail safe” in which if you do fall, this strap will catch you and keep you snug to the pole, which then you can stand up again and keep going. When you take the first step, you will feel the motors kicking in and you will feel less “weight” as you lift your leg. The motor is assisting with the ascending aspect of this climb. As you climb the utility pole, take it slow, one step at a time. It is not advised to “race” to the top as there is a greater chance of slippage or for something to break going at unsafe speeds..

There is a maximum number of degrees that the exoskeleton "knee" can bend as this will protect the user from over-extending their knee. Once at the top or when you want to take a rest, there is a lock system which can lock you into place. This will give you some sort of a seat to sit on while you catch your breath or while you are working on the pole. The battery should go into a power-saving mode to conserve its life as well. Periodically check the battery level if you will be on a utility pole for extended periods of time.

Once you have completed your job or the battery starts to run low, now it is time to descend. Unlock the lock that is keeping the exoskeleton still and slowly start to work your way down. Take one to two steps down, then move your strap down that is surrounding the pole and repeat. Once you are firmly planted back onto the ground, make sure to reach a location where you can safely dismount the exoskeleton. First, make sure to turn off the exoskeleton. Then simply undo all the straps attached to your body.

6.4 Storing

Before storing the exoskeleton until the next operation, it is important to have the exoskeleton cleaned between each use. This is important to make sure that the exoskeleton will last for as long as possible. The overall cleaning of the exoskeleton is quite an easy process. For the exposed aluminum poles, rub down these sections with water using a clean cloth, making sure to dry them entirely to avoid rust formation overtime. For the rest of the exoskeleton, the same can be applied. Gently rub down all exposed parts with water and then wipe clean. For the leather straps, you can use any leather cleaner that is on the market but be mindful not to get any of that product on the rest of the exoskeleton as complications can arise.

The exoskeleton can be stored in practically any condition. As long as it is in a place in which it does not get devastatingly hot or freezing cold, the exoskeleton will be okay to be stored. It is also best to keep it covered or away from natural elements such as the rain or the beaming sun. Now, the exoskeleton does not come with a storage box but having a cover blanket will help keep it dust free and away from the natural elements as well. With proper care and maintenance, this exoskeleton can last for a very long time. The shelf life of every part and the metal itself was designed to last for many years to come.

For the conclusion of senior design 2, the operating expectations and manual have not necessarily changed.

7 Project Summary and Conclusion

In this section we did wrap up the entire project, our findings, requirements, and the overall progression that was made.

This exoskeleton build started as a great idea last semester, to now be almost fully developed. The main idea behind this project is to help the linemen from The Florida Power and Light ascend and descend utility poles. This job is extremely strenuous on the body, so this company is investing heavily back into its employees and wanting to build something to help them out.

This Exoskeleton is being created to help support the lower body by using motors and sensors to help push the user wherever they need to go along the utility pole. It began development last semester by the last Senior Design team, and the design was created. Our job as the next cohort is to choose all the necessary parts, test, and assemble the entire exoskeleton.

Florida Power and Light being our sponsor, have provided many specifications and requests for when we actually assemble our exoskeleton. From having a locking mechanism to having a safety system that will keep the users safe in case of a failure or emergency. We made sure to carefully follow every instruction provided and to keep the users safety as our number one priority. We have made many progressional achievements in the development of the exoskeleton. We have chosen all necessary parts needed, such as the motors, batteries, sensors, control boards, and finalizing the exoskeleton design.

Since the very beginning, we have had strict deadlines that we have put onto ourselves. The first being submissions for our class such as having the divide and conquer assignment completed and the multiple different drafts. We also have set deadlines for certain progressions with the exoskeleton such as choosing the various different parts to have our component testing completed and printed. We were able to stay on task and complete everything as required. This is an exciting legacy project that we as a team find great passion in and are excited for the continuation next semester.

In the end of senior design 2, we were able to properly integrate electrical components to the exoskeleton and have a working prototype.

Appendix A - References

[1] Musculoskeletal symptoms among energy distribution network linemen
[2] https://www.asee.org/public/conferences/20/papers/5808/download
[3] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3274101/
[4] https://ieeexplore.ieee.org/document/5453854
[5] Technical Manual Series: Types of Brushless Motors
[6] https://www.ucf.edu/pegasus/power-move-onyx-exoskeleton/
[7] https://www.suitx.com/legx
[8] https://rewalk.com/
[9] https://www.indego.com/indego/us/en/home
[10] https://www.rexbionics.com/
[11] https://eksobionics.com/
[12]
https://www.aliexpress.us/item/2261800040038170.html?spm=a2g0o.detail.1000060.2.66f87c5crTTX75&gps-id=pcDetailBottomMoreThisSeller&scm=1007.13339.291025.0&scm_id=1007.13339.291025.0&scm-url=1007.13339.291025.0&pvid=7510697f-1e79-4707-bf32-7a93a76cd818&_t=gps-id%3ApcDetailBottomMoreThisSeller%2Cscm-url%3A1007.13339.291025.0%2Cpvid%3A7510697f-1e79-4707-bf32-7a93a76cd818%2Ctpp_buckets%3A668%232846%238113%231998&isseo=y&pdp_ext_f=%7B%22sku_id%22%3A%2220000000151179594%22%2C%22sceneId%22%3A%223339%22%7D&pdp_npi=2%40dis%21USD%2143.23%2132.42%21%21%21%21%21%402101d1af16686428154876313e8931%2120000000151179594%21rec&gatewayAdapt=glo2usa&_randl_shipto=US
[13]
https://www.amazon.com/dp/B07PNMYHFT/?coliid=I2C4KDKJ9XXCWQ&colid=3VR68FZ8BPG6Q&ref_=lv_vv_lig_dp_it&th=1
[14]
https://www.amazon.com/dp/B09QZ13KR9/ref=sspa_dk_detail_0?psc=1&pd_rd_i=B09QZ13KR9&pd_rd_w=KovXq&content-id=amzn1.sym.46bad5f6-1f0a-4167-9a8b-c8a82fa48a54&pf_rd_p=46bad5f6-1f0a-4167-9a8b-c8a82fa48a54&pf_rd_r=

1JGH84563W02YAG3QHM5&pd_rd_wg=wfAZj&pd_rd_r=2cc17338-c4ff-4212-ae40-0f99d87456b9&s=industrial&sp_csd=d2lkZ2V0TmFtZT1zcF9kZXRhaWw
[15]
https://flipsky.net/collections/electronic-products/products/flipsky-fsesc6-9-100a-base-on-vesc6-6-with-aluminum-anodized-heat-sink
[16]
https://www.alibaba.com/product-detail/OEM-Deep-Cycle-Li-on-12s4p_62331986511.html?spm=a2700.pccps_detail.0.0.5fdd246fpweDaQ
[17]Position estimation and control of compact BLDC motors based on analog linear Hall effect sensors
[18]
https://www.aliexpress.us/item/2261800040038170.html?spm=a2g0o.detail.1000023.7.60237a99SbnKbc&gatewayAdapt=glo2usa4itemAdapt&_randl_shipto=US