Below-the-Knee Exoskeleton

Conceptual Design Report

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DISCLAIMER

This report was prepared by students as part of a university course requirement. While considerable effort has been put into the project, it is not the work of licensed engineers and has not undergone the extensive verification that is common in the profession. The information, data, conclusions, and content of this report should not be relied on or utilized without thorough, independent testing and verification. University faculty members may have been associated with this project as advisors, sponsors, or course instructors, but as such they are not responsible for the accuracy of results or conclusions.

EXECUTIVE SUMMARY

For our team's capstone project, we are tasked to improve upon an existing design for an Ankle Exoskeleton through our client Dr. Lerner. Dr. Lerner's previous capstone team had built a working Ankle Exoskeleton that consists of a mechanical boot that consists of a boot-like frame that houses a motor and gearbox which provides leverage to the ankle joint. The motor located on the frame of the ankle draws power through wires running up the user's leg connected to a battery pack and microcontroller situated on a belt located on the waste of the user.

Our task as a team is to take all the components of the previous design and situate them all below the knee of the user. On top of making the design below the knee, we will be upgrading the motor, microcontroller, and battery. To fit all these components below the knee we will need to work through a couple of different steps. First, we need to redesign the frame of the boot. Doing this will give us more space to work in the battery and microcontroller below the knee. Some constraints we need to consider when making this design are; to not limit the range of motion, a universal design that fits all users, and light weight to not fatigue the user. Second, our design needs to have ingress protection for our electrical components. Our electrical components need to be resistant to dust and water to assure it accrues no damage while the user is operating the Exoskeleton. Some constraints that we need to consider while implementing ingress protection is again not limiting range of motion and a lightweight design. Our last step in our implementation is thermal and stress testing our design under strain. As the Exoskeleton is in use, the motor, microcontroller, and battery will heat up which might be uncomfortable for the user if we don't properly insulate each electrical part. To do this we have to find out how hot each component gets and then properly insulate each part to not reduce the effectiveness of the exoskeleton.

The entirety of our design contributions will include a new frame that will attach at the user’s calf and contain a new holder for the motor, PCB, and battery, and a protective covering for the electrical components to protect from daily wear and debris.

What we have done in our project so far has surrounded around the analyzation of the new parts we need and design of the frame to take these new parts. Based off what we analyzed from the last project, our new motor will be a Maxon ECX flat 32L with a 35:1 gear ratio. This new motor will give our Exoskeleton more stable torque. And based on our new constraints, the battery we will use will be a Cell E-Flite which will provide enough power to run our new motor. Our new design for the frame includes paneling behind the calve muscle that can house the battery and microcontroller. Current CAD models for our new design, as well as an initial prototype can be found farther down within this report.

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1 BACKGROUND

This chapter outlines the key deliverables, project goals, and success metrics essential for the redesign of the below-the-knee exoskeleton. The project focuses on eliminating the need for a waist-mounted battery and Arduino, with all components integrated below the knee. The design is aimed at supporting individuals with walking impairments, enhancing both daily function and physical therapy outcomes.

The chapter is organized into the following sections:

1. **Project Description** – This section discusses the overall description and background of the project. It included the intended goal, the sponsors, and funding/fundraising requirements.
2. **Deliverables** – This section discusses the critical outputs expected for the project, including the evaluation of motor specifications, battery analysis, motor mount design, and cover with ingress protection. These deliverables ensure the exoskeleton meets both the functional and environmental protection requirements.
3. **Success Metrics** – The criteria for project success are defined and linked to major technical milestones. This section highlights the importance of motor and battery performance, the structural integrity of the motor mount, ingress protection testing, system integration, and budget management. Each phase of the project will be rigorously assessed through calculations, simulations, and physical testing to ensure compliance with design requirements and functional efficiency.

1.1 Project Description

Our sponsor currently has a version of a below-the-knee exoskeleton, but it has the Arduino, and the battery stored in a pack at the waist. It was designed for the purpose of aiding in the gait of people with a walking impairment and can be used as a physical therapy method or in daily use. Our goal is to redesign the exoskeleton to incorporate all the aspects needed below the knee so that we can discard the belt portion. Our client is the head of the NAU Biomechatronic lab, Professor Zachary Lerner. Their lab develops lightweight wearable robotic exoskeletons to improve the movement of people with walking impairments. According to our client, our focus for the duration of this capstone is to evaluate the motor specifications and the mounting hardware design for the motor. We are also to research and calculate the needs for a new battery selection and create a mount for said battery and Arduino. Finally, we are to create a new cover and ingress protection design for all the above listed parts, Arduino, motor, and battery.

For this project, we have a budget of $4,000 dollars provided to us by WL Gore. On top of this funding, we have a fundraising goal of $400. We have begun a GoFundMe with the intent to advertise to our goal. Currently, we have raised $275.

1.2 Deliverables

The key deliverables for this project have several critical aspects that need to be taken into consideration for the design and functionality of the system:

1. **Class Deliverables:** This includes all required submissions as per the course outline, ensuring that the project meets the academic expectations and milestones outlined for evaluation.

2. **Motor and Battery Analysis:** A comprehensive analysis of the chosen battery and motor to confirm that they are the optimal selection and configuration. This analysis considers factors such as power requirements, efficiency, weight, and compatibility with the system's operational demands.
3. **Motor, Battery, and PCB Mount Design:** The motor mount design will be carefully engineered to securely integrate the motor into the overall structure using the analysis for power requirements and efficiency. This design ensures stability, proper alignment, and effective transmission of power from the motor to the rest of the system. We will also be designing a new location for the PCB and battery to ensure all necessary parts are below the knee, do not inhibit movement, and create a cohesive design.
4. **Cover and Ingress Protection Design:** The cover design focuses on safeguarding internal components while providing ingress protection (IP rating) against debris and water. This ensures durability and compliance with environmental protection standards, critical for the longevity of the system.

Together, these deliverables contribute to the overall functionality, safety, and durability of the project, ensuring that all mechanical and electrical components work cohesively and reliably.

1.3 Success Metrics

Success for this project will be assessed by meeting the key design requirements and ensuring the functionality of the exoskeleton without the waist belt, while keeping it lightweight and durable. The motor and battery must support daily usage for individuals with walking impairments. Each design phase will involve specific testing: calculations for power and torque requirements, finite element analysis (FEA) for mechanical components, and ingress protection tests for environmental safety. The overall design must be user-friendly and ergonomic, capable of functioning in a variety of real-world scenarios without compromising on safety or comfort. Budget management will also be a key success factor, ensuring resources are allocated effectively. Table 1 breaks down the success matrix used for the semester.

Table 1: Definition of Success

Objective	Definition of Success	Assessment Methods	Timeline
Motor and Battery Analysis	Identify a motor and battery combination that meets the power, torque, and endurance requirements for daily use.	Success will be measured through detailed motor specifications analysis, power output calculations, and battery endurance tests. Battery life must meet the operational requirements for daily physical therapy sessions (at least 30 minutes of use).	Weeks 1-3
Motor, Battery, and PCB Mount Design	Develop a durable, lightweight motor mount that securely houses the motor, PCB, and battery below the knee, without adding excessive weight or hindering movement.	Success is determined by CAD designs, stress analysis (FEA), and testing for vibration resistance and impact testing. This allows the team to ensure full daily use without the location of the mount inhibiting motion.	Weeks 5-9
Cover and Ingress Protection Design	Design a cover that provides protection for the motor and electronics, ensuring no environmental damage (debris, moisture) while maintaining easy maintenance access.	Success is defined by creating a cover that passes ingress protection tests (e.g., IP standards) and is easy to assemble/disassemble. Material selection must be lightweight and durable.	Weeks 9-12
System Integration (Motor, Battery, and Electronics)	Integrate the motor, battery, and electronics below the knee, ensuring smooth operation without the need for a waist belt.	Success is measured through functionality testing in real-life or simulated conditions. The system must operate for at least 30 minutes without malfunction, and overall weight must remain below a defined limit.	Weeks 12-15
Budget and Fundraising	Complete the project within the $4,000 budget and raise $400 through external funding.	Regular budget reviews and successful fundraising will indicate success. No budget overruns, and sufficient funds must be available for all necessary components and testing.	Ongoing

2 REQUIREMENTS

This section includes the customer requirements, which were mainly determined from reading research papers on both this and similar designs. They represent the criteria most important to the individuals using the device, which may be overlooked by the engineers. These criteria allow us to create a design that customers will want to use, rather than one that is simply functional, such as comfortability and affordability. The engineering requirements are the criteria which will allow us to create a design that will properly function for all intended users, such as torque and temperatures of electric components. The house of quality allows us to determine the correlation between these requirements; by weighting the customer requirements and assigning a value to the correlation between them and the engineering requirements, we can see the technical importance of each engineering requirements. This allows us to prioritize the engineering requirements with strong correlation to the most important customer requirements and compare these targets to existing devices which serve similar functions.

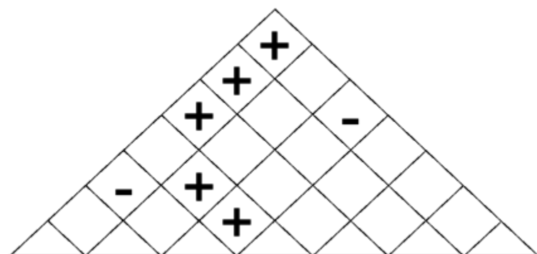
2.1 Customer Requirements (CRs)

The first customer requirement is durability. This will be important as the device will eventually be used in a customer's everyday life, and when walking outdoors, it is likely that eventually they may either kick or walk to close to an object and contact the device. Eventually we will design a protective cover, but along with this, the components need to be stable and close to the leg to avoid damage. A high range of motion is important as the device is designed to be assistive rather than simply an ankle brace. This means that the user will be able to use the motion of their ankle freely, and the device should be able to accommodate to that full range of motion. Once again, the device will eventually be used for everyday life such as hiking and recreational walking. Both adjustability and affordability are important as the device is intended to be accessible to a wide range of individuals who need the assistance. Because of this, the device is intended for those with cerebral palsy and other muscular deficiencies, it is crucial that the device is lightweight and can be easily attached to the user's feet for as long as they need while still allowing them to walk normally.

2.2 Engineering Requirements (ERs)

The most important engineering requirement was determined to be the torque produced by the drive system. The new motor to be installed produces a nominal torque of .103 Nm and is configured with a 35:1 reduction planetary gearbox, equaling a torque of 3.6 Nm. The system is designed to assist users with muscular deficiencies, namely cerebral palsy, and as a rehabilitative device rather than a prosthetic, the device does not necessarily need to support the full weight of the user. A high torque will, however, allow the device to be operated by a wider range of users of greater weights or less leg strength. Next in order of importance is the weight of the device. Again, with the target customer being users with cerebral palsy and muscular deficiencies, it is crucial that the device is lightweight enough to be used without hinderance, and to be used for long periods of time. We estimated that the device should be no more than 3 kg as to not negatively affect the user's gait. With a relative technical importance of 16%, the temperature of the motor needs to be low enough as not to cause discomfort or injure the user. The motor is mounted inches from the user's leg, right behind the calf cuff so a motor running hot could easily affect the user. Aside from injuring the user, an overheating motor could also cause permanent damage to the frame of the exoskeleton as well as the other electrical components nearby. The motor will be enclosed in a case both to prevent damage to the motor and to contain possible high temperatures produced. The ability to accommodate users of all weights and sizes are similar requirements, as the device is a rehabilitative tool, the exoskeleton should have the capacity to be used by any client who needs it. As stated, supporting users of all weights is a function of the system torque and has been improved with a new motor. Accommodation for users of different sizes mainly relies on the frame. The footplate and calf cuff are modular for users with different foot and calf sizes. The cuff mount on the current design is designed to be vertically adjustable, however there is only room to move about an inch. We are currently designing a system to expand the adjustability of this component. The battery capacity will be more important in the future, however, as of now the device is intended for lab use and the current run time of about 30 minutes is sufficient. The new motor we will install has a capacity of 910 mAh and will run for long enough while testing. Energy efficiency is the least important requirement, as stated, the current design is intended for lab use and the battery life does not need to be more than 30 minutes. In the future, a battery with a higher capacity will likely be selected so that the exoskeleton can be used day to day.

2.3 House of Quality (HoQ)



Customer Requirements \ Design Requirements	Importance (1-5)	Energy efficient	Accommodate different shoe sizes	High torque	Support users of all weights	Under 3 kg	Temperature of motor	Battery Capacity	1 Worst	2	3	4	5 Best
Improvement Direction													
Durable	3		3		6	6	6			C	AB		
High range of motion	5			9							B	AC	
Comfortable	4		3		3	3	3					A	
High battery life	3	9		6			9	9				B	
Adjustable	3		3		6							C	A
Lightweight	5			3		9						B	AC
Affordability	5							3		C	B		
Technical Importance: Absolute		27	30	78	48	75	57	42	A	Caplex Exo			
Technical Importance: Relative		8%	8%	22%	13%	21%	16%	12%	B	Utah Knee			
Design Competitive Assessment — Worst: 1								B	C	ETM Motor			
2					C		B	C					
3		AB		B		C	C						
4				C	A	B							
Best: 5		C	A	A		A							
Target Value		90	0.3	1000	90	2	70	1000					
USL		60	0.27		120	3	155						
LSL		30	0.22	500	30	1.5		500					
Units		mins	m	mNm	kg	kg	C	mAh					

Figure 1: House of Quality

3 Research Within Your Design Space

3.1 Benchmarking

When it comes to benchmarking, we began to research with the goal of revising and improving upon the current design. With the goal of a new motor and mounting design in mind, one of our state-of-the-art systems was a motor designed by the Electrifying Torque Motor, ETM. They are a company that has made a DC electric motor that is specifically for applying torque. This Motor could theoretically improve the efficiency of our design by consuming less energy than a brush or blushless motor.

The second state-of-the-art design is a full prosthetic made by the University of Utah. It was a fully prosthetic design made to be lighter and more compact. The AVT system used in the Utah knee project uses adjustable transmission to meet different speed and torque needs. It was made of a bigger DC motor connected to a 4:1 planetary gear among other design accommodations. This allowed for a reduction in the motor size and allowed for less torque due to low mass and inertia. The only downside was that it can only change transmission levels under minimal load. Overall, the entire prosthetic weighed 1.6 kg vs the average 3.4 kg.

Finally, there was the Humotech Caplex EXO-001. It was an exoskeleton that can be attached to the foot and was developed to aid in ankle injury recovery. It mounts to the user's shoe and is adjustable for multiple different sizes of shoe. It uses a cable system to apply torque with a max torque in Plantarflexion being 180 Nm and in Dorsiflexion being 1.5 Nm. The standard weight of the device was 1.4 kg.

3.2 Literature Review

3.2.1 Ryan Oppel: Proceedings of SYROM 2022 & Robotics 2022 - Chap. 23: Design of an Exoskeleton for Rehabilitation Ankle Joint [1]

Chapter 23 of *the Proceedings of SYROM 2022 & Robotics 2022* focuses on the design of an exoskeleton specifically for ankle joint rehabilitation. This chapter dives into the mechanical design and biomechanics of the ankle joint, highlighting the stresses experienced during movement and the importance of precise joint mechanics for effective rehabilitation. The proposed exoskeleton uses motorized joints and linear actuators to assist in ankle movement, aiming to improve mobility and support recovery for patients with ankle injuries. Learning about this technology can provide valuable insights into how exoskeletons are designed to mimic natural joint movements and enhance rehabilitation processes, which is crucial for anyone interested in biomechanics, robotics, or medical device innovation

3.2.2 Ryan Oppel: PID Control with Intelligent Compensation for Exoskeleton Robots [2]

PID Control with Intelligent Compensation for Exoskeleton Robots talks about using smart tweaks to make exoskeletons work better. It combines basic PID control, which helps keep things steady, with clever tricks like neural networks to fix issues and improve performance. This helps exoskeletons move more naturally and smoothly, which is super important for helping people in rehab or doing tough jobs. Learning about this can give me a good idea of how these wearable robots are controlled and why that's important for making them work well.

3.2.3 Ryan Oppel: The design, validation, and performance evaluation of an untethered ankle exoskeleton [3]

The design, validation, and performance evaluation of an untethered ankle exoskeleton is about making a small, battery-powered device to help people move their ankles better. This exoskeleton helps people walk more easily and uses less energy, which is great for both healthy people and those with movement issues like cerebral palsy. This can give me knowledge on how these devices are made to help people move better and recover faster, which is useful for biomechanics and robotics.

3.2.4 Ryan Oppel: Adaptive control strategies for lower-limb exoskeletons to assist gait [4]

This scientific paper explores how advanced control methods help exoskeletons support walking. These strategies adjust in real-time to the user's movements, making the exoskeletons more effective and comfortable. This shows how technology can enhance mobility for people with walking difficulties.

3.2.5 Ryan Oppel: A New Approach of Minimizing Commutation Torque Ripple for Brushless DC Motor Based on DC–DC Converter [5]

The article is about making brushless DC motors run smoother by reducing the jerky movements (torque ripple) they can have. This is done using a DC–DC converter to better control the motor's current. This improves the movement of the exoskeleton and makes it more controllable for the user.

3.2.6 Ryan Oppel: ASTM F48 Formation and Standards for Industrial Exoskeletons and Exosuits [6]

These are the industry standards for making an exoskeleton and ensure that exoskeletons are safe, effective, and reliable. This committee, formed in 2017, develops standards for the design, performance, and use of exoskeletons in various fields like industry, healthcare, and the military. Learning about these standards is important because it helps me understand the best practices and safety measures needed to develop and use exoskeletons. This knowledge is crucial for making these devices, as it ensures they meet high-quality standards and are safe for users.

3.2.7 Ryan Oppel: Opportunities and challenges in the development of exoskeletons for locomotor assistance [7]

This article looks at the progress and hurdles in making exoskeletons that help people walk. It talks about how these devices can improve movement for people with walking difficulties and the technical and clinical challenges that come with it. Learning about this helps me understand the real-world applications and obstacles in developing exoskeletons, which are important for biomechanics and robotics. It shows how far we've come and what still needs to be done to make these technologies more effective and accessible.

3.2.8 Ryan Oppel: Aerospace specifications metal data sheet for Aluminum Alloy 7075 – O (ss) [8]

This is a materials data sheet for specifically Aluminum Alloy 7075 – O (ss), a high strength to weight ratio alloy which we will be using for our motor mounting brackets. "A material data sheet (MDS) is an important document that provides key information about a material's properties, like its strength, durability, and how it behaves in different conditions (temperature, moisture, etc.)." this information is important for us to know because this info will help us calculate the factor of safety's we need for our mounting hardware and anything else we might use this material for within the build.

3.2.9 Ryan Oppel: 3D printing strength: How to 3D print strong parts [9]

The article explains how to make 3D prints stronger by choosing the right infill settings. Infill is the internal pattern inside the print, and it affects how strong the final object is. The article says that a denser (more filled) infill makes the print stronger, but it also uses more material and takes longer to print. Different patterns, like grid or honeycomb, can also change how strong the print is.

3.2.10 Ryan Oppel: Introduction to SOLIDWORKS simulation - finite element analysis [10]

This source was used to help understand better how to operate SolidWorks to help find out specifically how to operate its FEA feature. We used the FEA feature to help us calculate the loads being presented on the motor mount and surrounding brackets to make sure that the material we were using would hold the motor and not hurt the user in any way. The SolidWorks tool also helped us to find any weak point in our design by showing potential breakpoints in our design.

3.2.11 Alex Schell: Kinematics and Kinetics of the Foot and Ankle during Gait [11]

This article discusses the role of the foot, ankle, and joint in the gait, as well as the phases within the cycle of the gait. It goes over how this is considered when building braces and exoskeletons. It begins by breaking up the stages of the gait as well as the importance of different joints in the forces applied to the foot. This analysis on the forces and applying it to the control of the robotics system to accomplish a simulation of the gait. It concluded that the most important aspect of loadbearing in the lower body focuses on the foot. Its importance in this demonstrates that our need to understand its function and analyze the mechanics in the foot allows us to look at opportunities to alter or correct the gait through robotics. New motion capture technology allows us to better analyze these measurements and advances modeling approaches. This article allows us to better understand the importance of the foot during the different stages of the gait and aided in calculations.

3.2.12 Alex Schell: Cadaveric Gait Simulation [12]

This article outlines the way Dynamic gait simulation, DGS can simulate the full kinetics and kinematics of gait, making it more useful for modeling walking dynamics. It takes calculations and imaging done on an actual gait and applies it using cadaveric models. It allows for a greater understanding of the forces, tendon and otherwise, degrees of freedom, and kinematics. It allows scientists to replicate the dynamic of the foot. This article allows us to get a better idea of the modeling techniques used in our calculations and thus the design of our exoskeleton.

3.2.13 Alex Schell: Developments and clinical evaluations of robotic exoskeleton technology for human upper-limb rehabilitation [13]

This article described exoskeleton advancements and focuses on improving joint control and muscle activity for rehabilitation using EEG, EMG, and other sensors to enhance accuracy and motor stability. This allows scientists to provide real-time physiological measurements. However, challenges remain with weight, power consumption, limited torque, bulky designs, and high costs, which hinder practical usability. This article allows us to get a better idea of current sensors used in the creation of prosthetics for the purpose of joint control.

3.2.14 Alex Schell: Toward High-Performance Lithium–Sulfur Batteries: Efficient Anchoring and Catalytic Conversion of Polysulfides Using P-Doped Carbon Foam [14]

This article discusses the benefits and downsides of Lithium-Sulfur Batteries. This includes high energy density and good energy storage. On the downside, the insulating sulfur can limit operation. It offered a few options to increase efficiency: including limiting porous carbon, which enhances conductivity, but reduces battery life and charge efficiency. PCF can also have high discharge and good life cycle. The microporous nature makes it good for high performance LSBs. This article helps us get a better idea of the types of batteries that can be used for our specific goals of high energy storage and high battery life.

3.2.15 Alex Schell: A Lightweight, Efficient Fully Powered Knee Prosthesis with Actively Variable Transmission [15]

This article described a group of roboticists at the University of Utah who worked to develop a lower weight fully powered prosthesis, equivalent to a passive prosthesis. It used Actively Variable Transmission (AVT) which adjusts transmission to meet different speed and torque needs. This prosthetic used DC motor, a planetary gear, leadscrews, bearings, and an incremental encoder for position feedback. This allowed for a reduction in motor size because it required less torque because of low mass and inertia. The downside though, is that it can only change transmission under minimal load. The AVT system was a logical choice to lower the overall weight of a machine and could be applied to lower the weight of our prosthetic since we are already adding weight in the form of the battery pack and Arduino.

3.2.16 Alex Schell: F3527 Standard Guide for Assessing Risks Related to Implementation of Exoskeletons in Task-Specific Environments [16]

This article highlights the risk assessments that must be considered for creation of exoskeleton. It also mentions the guide to not override existing laws and regulations.

3.2.17 Alex Schell: The Essential Guide to Selecting Batteries for Robotics [17]

This article describes the usage of different types of batteries for certain necessities in robotics, including powering sensors, microprocessors, and motors. The battery must match power, voltage, and current specifications, determining that LiFePO4 batteries stand out for long cycle life and reliability. This allows us to look at more options for batteries, which is one of our team deliverables.

3.2.18 Alex Schell: Batteries for Electric Vehicles [18]

This article discusses the different types of batteries used in electric vehicles. They are preferable due to the high power-to-weight ratio, as well as high energy efficiency. This allows us to gain a better idea of a battery that offers high efficiency, since it is used to power a car. The downside is the size, but if we can find a battery that emulates these factors, it would be a beneficial choice for our design.

3.2.19 Alex Schell: Convection Heat Transfer [19]

This article discusses the properties of heat transfer through convection. It discusses the difference in air flow over a flat plate versus a cylindrical object. It also contains an in-depth overview on the formulas that go into calculating heat transfer across the different types of objects. This was useful to the project to allow us to do an in-depth thermal analysis on different parts of our design. 6.3.1 and 6.3.2 shows said thermal analysis on our motor cover design, and we also plan to perform an analysis on the PCB mounting as well.

3.2.20 Alex Schell: Properties of Air at atmospheric pressure - The Engineering Mindset [20]

This article goes over the different properties of air at different temperatures. This covers density, ρ, dynamic viscosity, μ, specific heat capacity, cp, thermal conductivity, k, and Prandtl number, Pr. This was useful to my project for the thermal analysis conducted in section 6.3.1 and 6.3.2.

3.2.21 Alex Schell: IP Ratings [21]

This article discusses the standards assigned to different levels of ingress protection. This is useful to our project because one of the main tasks assigned to us is to create a cover for the motor, PCB, and battery. As of right now, we are estimating a 5 on the level of solid foreign objects, or protected against dirt, and a 1-4 on the scale of water, or protected against water drops to light splashing water.

3.2.22 Nick Watkins: Prosthetic forefoot and heel stiffness across consecutive foot stiffness categories and sizes [22]

This article focuses on prosthetics and the ideal stiffness based on the user's weight and activity level. Our design is not a prosthetic; however, this can help us to determine the ideal flexibility for the foot plate for the user's comfortability as well as assistance in walking.

3.2.23 Nick Watkins: Robotic Emulation of Candidate Foot Designs May Enable Efficient, Evidence-

Based, and Individualized Prescriptions [23]

This article is also focused on prosthetics, explaining a system used to emulate the sensation of wearing prosthetics to aid in fitting. This can be sued for the exoskeleton when researching gaits and walking patterns.

3.2.24 Nick Watkins: F3528-21 Standard Test Method for Exoskeleton Use: Gait [24]

This standard is incredibly relevant to our design, it outlines the methods of evaluating the safety and performance of exoskeletons, specifically those assisting in a user's gait, including medical rehabilitation, recreational hiking, and military use. The tests include an endurance test, a speed test, and a balance test and can be used to provide manufacturers with information about the usefulness of their designs.

3.2.25 Nick Watkins: G-Exos: A wearable gait exoskeleton for walk assistance [25]

This article explains the process of creating an ankle exoskeleton designed for stroke patients, to assist dorsiflexion, plantarflexion, and ankle stability.

3.2.26 Nick Watkins: The Mechanical Functionality of the EXO-L Ankle Brace [26]

This article analyses the functionality of an elastic ankle brace, designed for sprains, to limit only the motion of combined inversion and plantar flexion.

3.2.27 Nick Watkins: Pilot evaluation of changes in motor control after wearable robotic resistance training in children with cerebral palsy [27]

This article discusses a prior stage of our device, however rather than usage as an assistive device, the system was used for resistance training on users with cerebral palsy.

3.2.28 Nick Watkins: Does Ankle Exoskeleton Assistance Impair Stability During Walking in Individuals with Cerebral Palsy? [28]

This article is about the state of the device we are working on, from several years ago. It discusses the stability and gait analyzed from testing an exoskeleton designed to assist plantarflexion, in individuals with cerebral palsy.

3.2.29 Nick Watkins: F3323-24 Standard Terminology for Exoskeletons and Exosuits [29]

This standard covers terminology associated with exoskeletons and exosuits, including labeling, test metrics, and test methods.

3.2.30 Nick Watkins: F3474-20 Standard Practice for Establishing Exoskeleton Functional Ergonomic Parameters and Test Metrics [30]

This standard explains recommended approaches and variables for assessing the function of exoskeletons. Variables include joint movement, posture assessment, and functional movement.

3.2.31 Nick Watkins: Ankle Exoskeleton Assistance Can Affect Step Regulation During Self-Paced Walking [31]

This article discusses the effect of exoskeletons on gait. Unimpaired individuals were recorded walking with and without exoskeleton assistance, with their step width, walking speed, and cost of transport analyzed.

3.3 Mathematical Modeling

3.3.1 Center of Mass – Alex Schell: To begin our calculations, we did a simple Center of Mass calculations. The main position was in the end stage of the gait where the foot is just pushing off the ground and beginning the swing stage. The calculations were based off the measurements of a teammate's foot, with the assumption that the ankle and foot makeup about 6.5% of the weight of the human body. Figure 2 demonstrates the diagram of the foot on a grid system, marking the center of mass with a red dot at point (-3.95, 8.91). This calculation of center of mass can be used to determine where to place the payloads, aid in stability, and predict motion, such as angular velocity, Potential Energy, and Kinetic Energy.

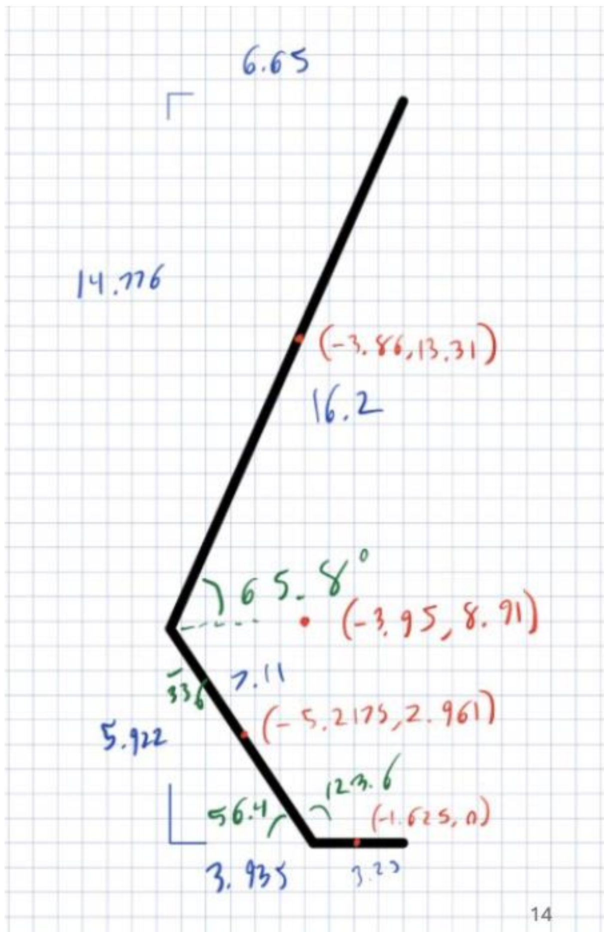


Figure 2: Center of Mass

3.3.2 Mathematical Modeling of the Foot – Nick Watkins: The next calculation was to model the forces of the foot at the location where force is the greatest. We assumed the weight of 200lbs (90kg) and a shoe size of 10.5. Figure 3 demonstrates the free body diagram of the forces below the ankle. We were able to calculate ground force, 1068N, force at the ball of the foot, 958N, and the work, -45.12J. Figure 4 demonstrates the method with which we found the above values. The calculations for work were then used for the next set of calculations, 3.3.2.

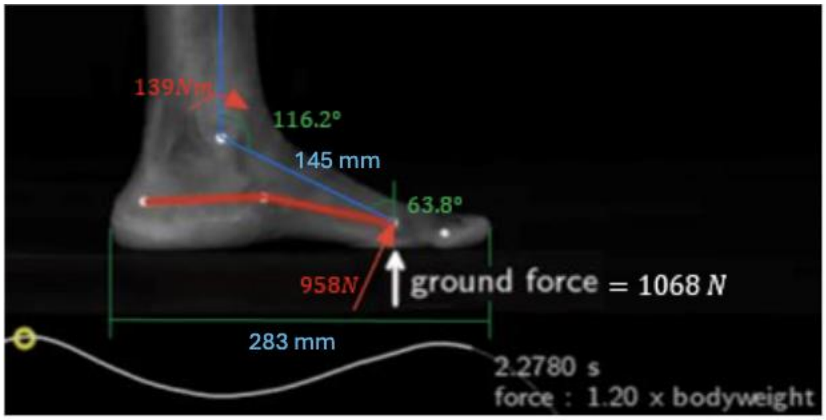


Figure 3: Free Body Diagram

(Yale Biomechanics and Control Lab, 2020)

Assuming: 200 lbs (90 kgs)
Shoe size men 10.5 (283 mm)

Calculating the peak torque produced by the ankle

$$F_g = 1.2 * 90\ kg * 9.81\ m/s^2$$
$$F_g = 1068\ N$$

$$F = 1068\ N * \sin 63.8°$$
$$F = 958\ N$$

$$\tau = 958\ N * \frac{145\ mm}{1000}$$
$$\tau = 139\ Nm$$

$$W = \tau * \Theta$$
$$W = -139\ Nm * (116.2° - 97.6°) * \frac{\pi}{180}$$
$$W = -45.12\ J$$

Equation 1: Mathematical Modeling Calculations

3.3.3 Torque Output by Motor onto motor mount – Ryan Oppel: For this Analysis of the motor mount, what we are looking to find is the stresses applied from the motor to the mount and all other components. We are working with an ECX FLAT Maxon motor so to start with this analysis we must define the amount of force that this motor will have on the mount. Our mount for the motor consists of two parts that will be screwed on to the motor, a carbon fiber tube, and each other. These two parts that create the mount of the motor will also hold a cover for the motor which will also be screwed into each other. Another variable which is important to know when doing a stress analysis is the type of material used for the mounts and other components attached to the motor and or mounts. For these mounts, our client, Dr. Lerner picked out the material that we will use. The material for these mounts is 7075 - O (ss) Aluminum alloy. This is the type of material which he has used in the past for his exo-skeleton projects, and it has shown that this material is the perfect balance between strong, lightweight, and thermally conductive which will help us with thermal management of the motor later down the line. The last criteria to understand to perform a stress analysis will be the physical dimensions itself. Because our parts are dimensionally complex, I will be using SolidWorks software to visually show the stresses on the material. I believe it is important to bring up this variable because in the design phase of the project the team made sure that we design parts to have as little of a weak point as possible, we did this by filleting holes and edges and creating connecting parts where we can ensure structural integrity. While we are doing some of these calculations through SolidWorks, we still are doing a considerable number of calculations by hand. In this analysis we will be ultimately finding the factor of safety of our motor mount (FoS). In this we must calculate many things starting with the force the motor will displace onto the mount. Since the motor has an attached gearbox, we will be finding the torque in which that gearbox will apply. then we must find the mounting points on the mount and find the forces that will be applied to each of them. After that we will find the weakest point in the mount and do a force analysis there where we will then be able to calculate our factor of safety with our known material.

To start out with our calculations, I must first find the amount of torque that the motor will apply to the motor mount. I found this information on the manufacturer's website. for the ECX FLAT Maxon motor we find that the nominal torque that this motor will provide at maximum power will be 103 mNm. with this information I will then calculate how much torque will be applied to the motor mount by using a simply gear-ratio equation with our gearbox which is a 1:35 gear ratio.

$$\text{Output Torque} = \text{Input Torque} \times \text{Gear Ratio}$$

$$\text{Output Torque} = 103\,\text{mNm} \times 35 = 3605\,\text{mNm}$$

$$3605\,\text{mNm} = 3.605\,\text{Nm}$$

Equation 2: Torque Output Equation

With this value, I must conceptually understand how these forces will be applied to the mount itself. Now that I know the value at which the motor is applying torque to the rest of the mount, I must find out what points are being displaced on in the mount, find their distance from the displaced torque and how many points of contact there are.

The motor is mounted to the bracket by four screws that are 3mm in diameter which are situated exactly 13mm away from the center of the motor shaft. With this information I can calculate how much force each mounting point will experience with a simple torque equation.

$$T = F \cdot r \implies F = \frac{T}{r}$$

$$T = 3.605\,\text{Nm} \qquad r = 13\,\text{mm} = 0.013\,\text{m} \qquad F = \frac{3.605}{0.013} = 277.31\,\text{N}$$

Equation 3: Torque Stress Equation

With this number I then divided the total force by 4 to find out how much each mounting force will experience which gave me a final number of 69.33N. the only other stresses applied to the mounts are the downward force of the weight of the motor cover and mounted motor which is attached to a chain which came out to approximately 2N of force.

Now with the torques known on each mounting point for the motors to mount onto the brackets I then did a finite element analysis in SolidWorks of all the forces applied to the motor mounts

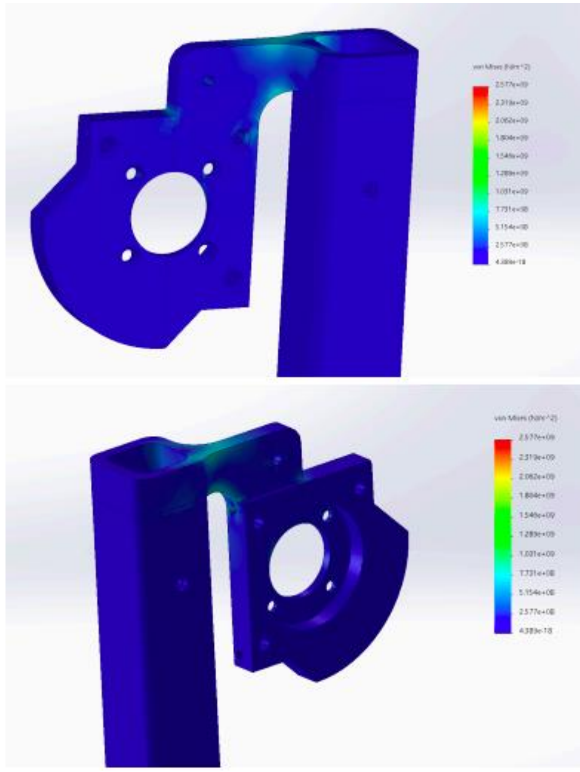


Figure 4-5: visuals of the FEA applied to the motor mounts with known variables

As we can see, where the connection is between the motor mount and the carbon fiber tube, the design comes to a bottleneck which is where we can see where our biggest calculated force peaks. according to SolidWorks, the max amount of stress that was applied to our design was 1.042*10^7 N/m^2 which comes out to approximately 10.42MPa.

According to the ASM Material data sheet, 7075 - O (ss) Aluminum alloy has a yield strength of approximately 145MPa. With these new values I can now calculate the factor of safety for our motor mounts.

The equation for Factor of Safety is:

$$\text{FOS} = \frac{\sigma_{\text{yield}}}{\sigma_{\text{applied}}}$$

$$\text{FOS} = \frac{145}{10.42} \approx 13.91$$

Equation 4: Factor of Safety

$$T_{\text{output}} = T_{\text{input}} \times \text{Gear Ratio}$$

Equation 5: Torque Output Calculation

$$\text{Total Efficiency} = (\text{Stage Efficiency})^{\text{Number of Stages}}$$

If we assume a 2% loss per stage and a multi-stage gearbox with 3 stages to achieve the 89:1 ratio:

$$\text{Total Efficiency} = (0.98)^3 \approx 0.94$$

Equation 6: Total Efficiency Calculation

3.3.4 Gear Ration and Stress and the Motor – Alex Schell: If torque output is labeled as the torque needed at the ankle and torque input is measured at the motor, both calculations were solved in the previous presentation. Input was calculated at 3.7 Nm due to the specs of the motor, and the output was 139 Nm. Due to these numbers, we can assume we need a gear ratio of 38:1. With the equations listed in equation 7 and the torque being 3.7 Nm and the radius of the shaft, as designed in SolidWorks, being 3 mm, the stress is calculated at 8.74 E7 MPa

Stress at the motor

$$\tau = \frac{T*r}{J}$$

τ = Stress
T = Torque
r = radius of the shaft

$$J = \frac{\pi r^4}{2}$$

J = Polar moment of inertia

Equation 7: Stress Calculations

3.3.5 SolidWorks Simulation – Alex Schell: We performed a simulation to show the stresses and the life cycle of the current motor mount, which is one of the items we are tasked with redesigning. The current location is located at the back of the model, prone to being bumped on surrounding objects. There is no water resistance or protection against debris, which is another customer requirement. The current placement is prone to high stress and fracture. Figure 6 demonstrates the Von Mises stresses based on a force of 15N. Figure 7 demonstrates Life Cycle based on 15N after 1000000 cycles.

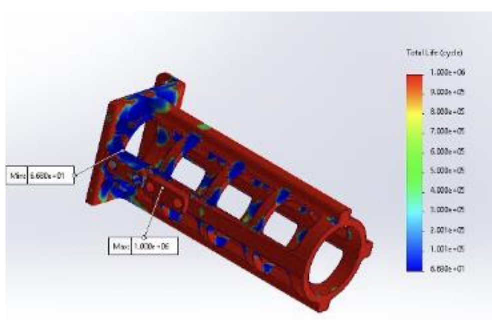


Figure 6: Von Mises Stress

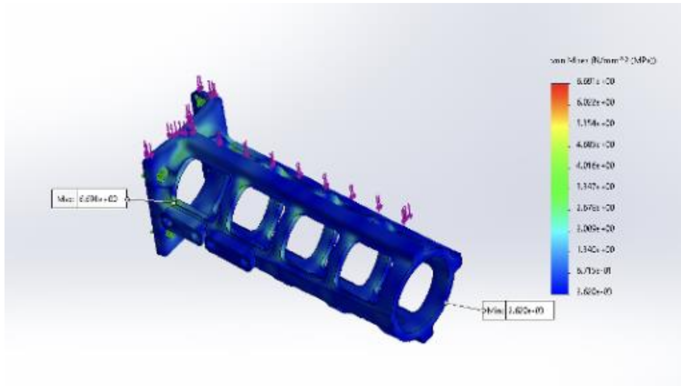


Figure 7: Life Cycle

4 Design Concepts

4.1 Functional Decomposition

Figure 8 depicts the functional decomposition our team will be following throughout the year. It breaks up the deliverables needed and analyzes the route that we will take to ensure that our deliverables are up to the standards of our client's requirements and successful with the overall design.

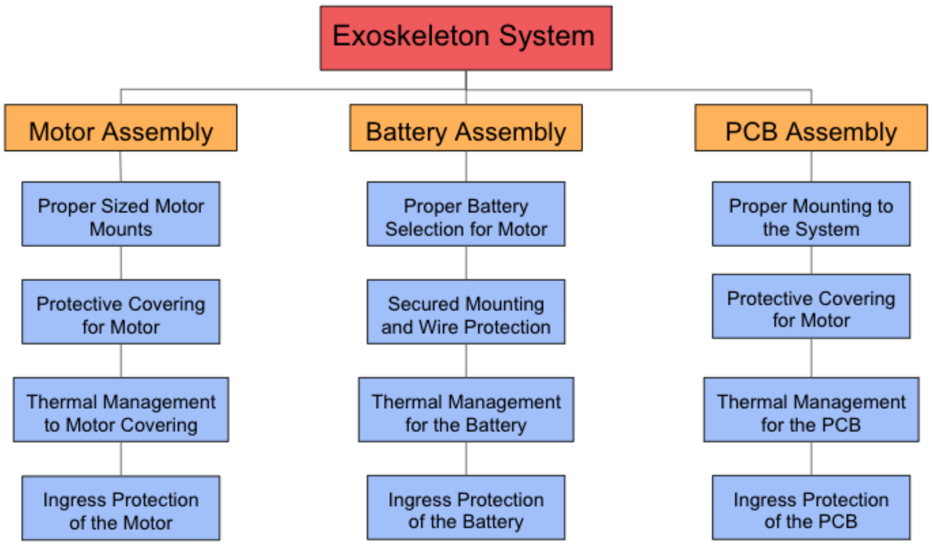


Figure 8: Functional Decomposition

4.2 Concept Generation

At the current stage in the design process, our goal is moving both the battery and controller board onto the exoskeleton itself. Currently, the battery, microcontroller, and PCB controlling the exoskeleton are mounted on a belt that the user must wear while operating. This system is sufficient for a physical therapy or testing environment, but the final design will need to be capable of operating under everyday use. A new battery must be selected as well, as the new motor has a higher power draw, and the power life of the system will need to be extended.

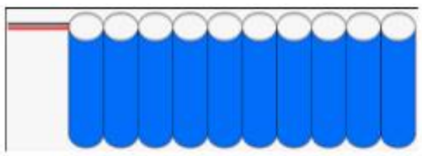
 *Figure 3500mAh 10A Protected Lithium Ion*	 *Figure Dantona L148A26-4-18-3WA3 Lithium-Ion Battery Pack*
 *Figure Li-Ion 21700 Battery*	 *Figure 2p3s 10.8v 6400Mah Lithium Battery Pack*

Figure 9: Battery Selection

After careful consideration, our team has chosen the E-Flight 22.2V battery. first concept places the battery on the frame of the exoskeleton. This separates the battery from other electronics as well as the user's skin, which will prevent the components overheating and the battery burning the user.

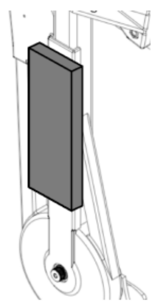


Figure 10: Battery mounted on the frame

This concept mounts the battery on the back of the motor, which will keep the center of mass as high as possible and will not contact the user's leg.

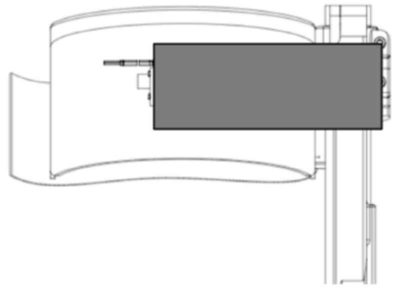


Figure 11: Battery mounted on the motor

Figure 12 requires multiple battery cells instead of a single battery and holds these cells on the outside of the cuff. In addition to the placement away from the user's leg, the center of mass of the battery is at the highest possible point.

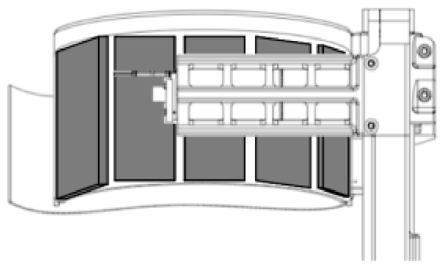


Figure 12: Battery cells mounted on the cuff

The final concept mounts the battery cells in a heat-resistant sleeve under the cuff. The cells are far from the motor while also keeping the center of gravity high.

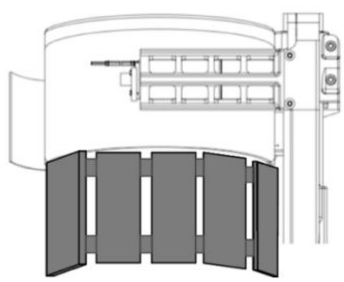


Figure 13: Battery cells mounted under the cuff

4.3 Selection Criteria

Our teams selected parts consist of the motor, the battery, and the frame for how we will compile the parts. Each part had its own weight system depending on their purpose and how they were used in the exoskeleton.

While our team was doing an analyzation of the motor and the specifications, our client (Professor Lerner) had already picked out a motor for us to use. So instead of comparing motors quantifiably, I will rather show through calculations why this motor is a better fit for our exoskeleton than the previous motor.

Old: EC-4pole

Nominal voltage	36 V
No load speed	16300 rpm
No load current	109 mA
Nominal speed	14900 rpm
Nominal torque (max. continuous torque)	43.7 mNm
Nominal current (max. continuous current)	2.16 A
Stall torque	612 mNm
Stall current	29.1 A
Max. efficiency	88 %

Figure 14: Factory Specifications of old motor without gearbox

New: ECX Flat

Nominal voltage	24 V
No load speed	10600 rpm
No load current	179 mA
Nominal speed	8100 rpm
Nominal torque (max. continuous torque)	103 mNm
Nominal current (max. continuous current)	4.24 A
Stall torque	438 mNm
Stall current	51.6 A
Max. efficiency	89 %

Figure 15: Factory Specifications of new motor without gearbox

As shown in the motor spec sheets (Figures 14 and 15), our new motor is specified for torque. The ECX Flat has roughly 2.4X more continuous torque than the EC-4pole. This allows us to increase our applied force from the Exoskeleton or we could keep the same amount of torque but drastically boost our efficiency. The ECX-Flat does, however, take approximately 2.16X more continuous current to run, which is one downside but does not outweigh the good. This is the reason why we are using a different battery to adjust to these new parameters.

Our frame configuration is mainly based around the batteries and hox we will implement them. The microcontroller we are using is very small and we have space for it in our frame already, so we did not focus on it when designing a new frame. Our criteria for our frame design are a high center of gravity, heat transfer to the user and other electrical components, and protection for our cell batteries. The reason for a higher center of gravity is because the higher we can get all the weight up the leg, the less of a moment force the exoskeleton will have on the user's hip and knee joint. To quantify each criterion, we gave each a weighted value of importance based on the customer requirements that the client gave us with protection of the cell batteries. After calculating our weighted values, our best design came out to be Battery cells mounted under the cuff as seen in figure 13. This design is the best of all the criteria, being high up, away from the user and separate from other electrical components and in a low-risk area for damage.

4.4 Concept Selection

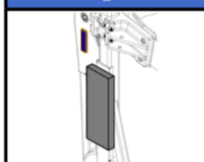
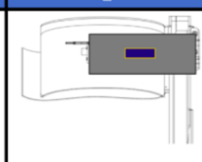
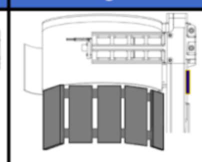
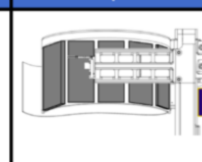
		1	2	3	4
					
High Center of Gravity	1	-	+	S	+
Heat Transfer to Skin	3	+	+	-	S
Heat Transfer to Electronics	4	+	-	+	-
Protection	5	-	-	+	+
Σ		1	-5	6	2

Table 4-A: Battery position concept selection

For the four battery placements, we had four selection criteria: high center of gravity, heat transfer to skin, heat transfer to electronics, and protection, in order from least to most important. Keeping the center of gravity closer to the knee will make it easier for the user to move their leg, as work required increases with distance from center of rotation. This is relevant as the clients will have existing muscular deficiencies; however, the importance is low since the weight of the battery is minor compared to the weight of the entire system. Heat transfer to skin is a consideration as batteries can get hot with extended use, and the device is intended to be used for hours at a time, although this can be negated with insulation. Heat transfer to electronics refers to the proximity to the motor, as both components get hot with use, and one has the likelihood of causing the other to overheat. Batteries, when exposed to excessive heat consistently, can lose function, or swell and eventually explode. Lastly, "protection" is rated the highest. As stated in Concept Generation, eventually, a protective shroud will be designed and installed to cover the components, so the system needs to be low profile to fit under the cover. Additionally, because this device will eventually be used in real life, likely outdoors, the design needs to avoid parts sticking out far from the assembly, which would make damage more likely if walking too close to any obstacles. Based on these criteria, the design which places the battery under the cuff and the Arduino on the frame ranked the highest. This design has a neutral center of gravity, maintains distance between battery and motor, and keeps the battery as close to the leg as possible. The only criteria this design failed was heat transfer to skin, however this can be resolved by placing the battery within a heat-resistant sleeve. This design

assumes the power source will be several battery cells, however, therefore since the battery selection has already been made the design may need to be reworked to accommodate for different sized and shaped batteries.
Based off our selection criteria, our team has compiled our first prototype. Through the selection process we were able to rule out some designs which could cause us issues.

Figure 16: Assembly of our first prototype

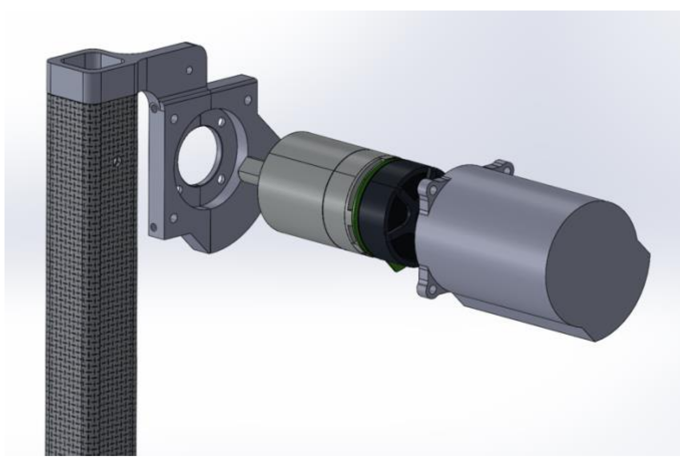


Figure 17: Assembly of our motor mount and protective covering

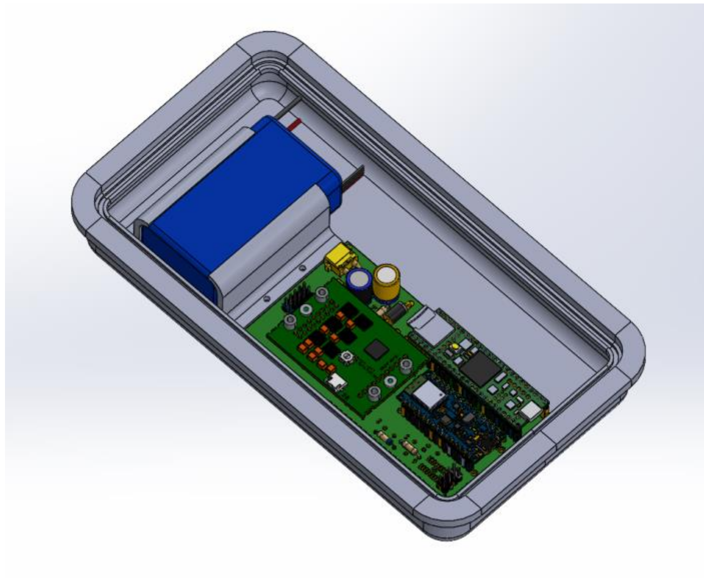


Figure 18: Assembly of our Battery/ PCB Protective Covering

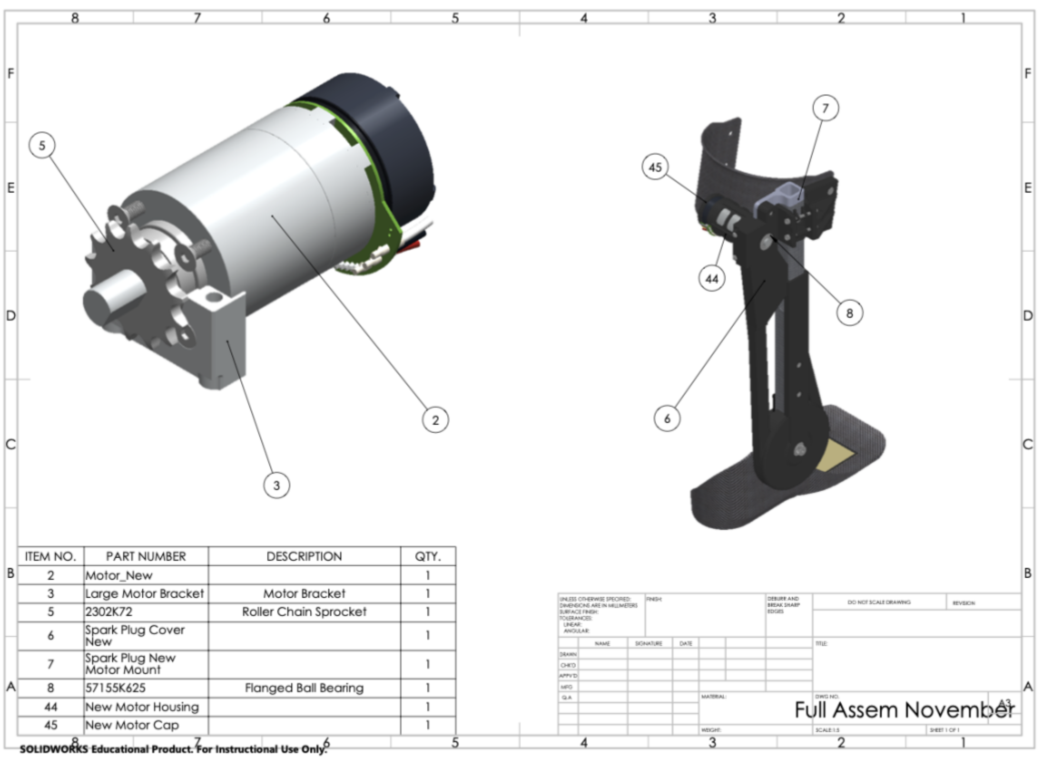


Figure 19: Final Concept Drawing and BOM

5 Schedule and Budget

5.1 Schedule

As the schedule for this semester ends, the team began to look at the necessary tasks to get to the final product by the deadline in May of 2025. The team is on track to be able to complete the final design based on the outcome of our initial prototype. Currently, we still need to conduct a few more tests on the overall location of the current mounts and integrate thermal and ingress protection. Figure (20) shows the Gantt chart with the status of the team for the current semester, while figure (21) shows the tentative schedule for the upcoming semester.

2	Major Deadlines 1st Semester																				
WBS Number	Task Title	Task Owner	Start Date	End Date	Duration	% Done	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2.2	Initial CAD Design	Nick W	9/30/24	10/28/24	28	100%															
2.1	1st Protype Demo	Alex S	10/28/24	11/13/24	15	100%															
2.2	Final CAD and BOM	Nick W	10/11/24	12/3/24	52	65%															
2.3	2nd Protype Demo	Alex S	10/11/24	12/4/24	53	10%															
2.4	Analysis of Prototype	Team	12/4/24	12/7/24	3	10%															
2.5	Purchase of Parts	Ryan O	10/11/24	10/26/24	15	80%															
2.6	Test 1st Prototype	Alex S	11/13/24	11/24/24	11	75%															

Figure 20: Gantt Chart of Semester 1

3	Major Deadlines 2nd Semester																				
WBS Number	Task Title	Task Owner	Start Date	End Date	Duration	% Done	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
3.1	Test 2nd Prototype	Team	12/4/24	12/7/24	3	0%															
3.2	Analysis of 2nd Prototype	Alex S	10/11/24	10/26/24	15	0%															
3.3	New CAD based on Analysis	Ryan and Nick	11/13/24	11/24/24	11	0%															
3.4	New (3rd) Prototype	Team	12/4/24	12/7/24	3	0%															
3.5	Test and Analyze Protype	Alex S	10/11/24	10/26/24	15	0%															
3.6	Desing and Build Final	Team	11/13/24	11/24/24	11	0%															

Figure 21: Gantt Chart of Semester 2

As for the breakdown of the individual tasks over the year. We are mostly following the guidelines set forth by the class, completing major prototypes by the deadlines. But we have separated out our tasks and therefore the semester into three different tasks. They are battery selection, motor analysis, and cover and ingress protection for the motor, PCB, and battery. This covers the location they are to be placed on the overall exoskeleton, as well as how it will be protected against debris and water, as well as protection from heat production. Figure 22 demonstrates the work breakdown structure throughout the year, as well as an overview of budget and time for each section. These three tasks are again broken up between CAD designs, prototype creation, analysis and repeat to create a final working product.

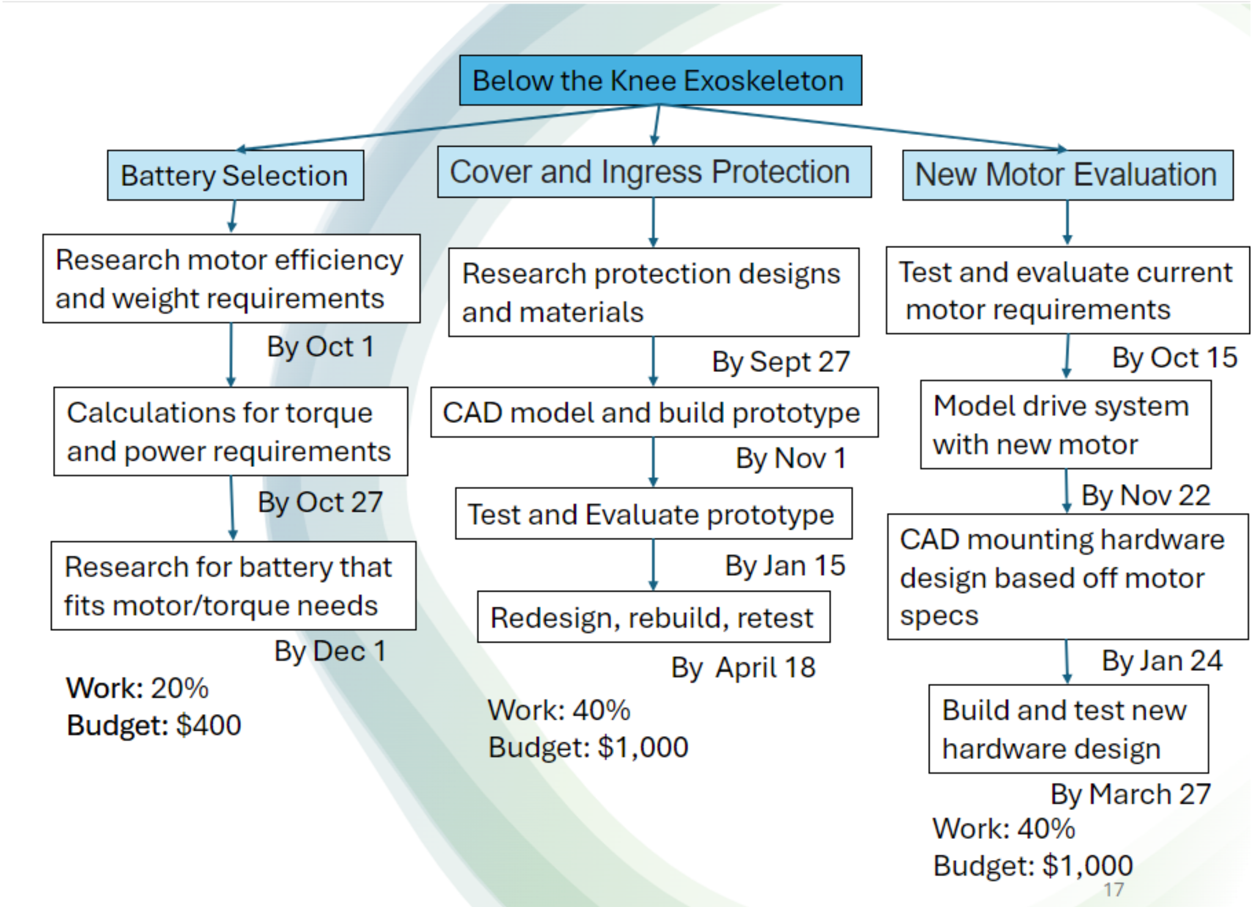


Figure 22: Work Breakdown Structure

5.2 Budget

Budget	
Fund Location:	Expenses:
W.L Gore Funding	4075
800cc Onyx Filament	-190.87
150cc Carbon Fiber Filament	-565.01
E-Flight 22.2V battery	-53.29
Maxon ECXFL32L KL A HTQ 24V (X2)	-599.51
Fluorine Rubber O-Rings 42mm OD 2mm Width	-16.9
O Rings Nitrile Rubber 185mm OD 2mm Width	-16.91
total:	2632.51

Table 5-A: Budget of current Expenses

Budget	
Fund Location:	Expenses:
Rest of W.L Gore Funding	2632.51
More Carbon Fiber Filament	-100
Machined Aluminum Parts	-300
PCB	-500
E-Flight 22.2V battery	-53.29
new Spark Plug Assembly	-1500
Total:	179.22

Table 5-B: Budget for future Expenses for Build/ Prototyping

5.3 Bill of Materials (BoM)

Part:	Cost:	Materials:	Purchased or Manufactur	Vender:	Part #:	Lead Time:
8mm Steel Ball Bearing	N/A	-	Provided by Client	-	-	-
Medium-Strength Steel Nylon	N/A	-	Provided by Client	-	-	-
Stainless Steel Button Head Torque Screws	N/A	-	Provided by Client	-	-	-
Alloy Steel Socket Head Screw	N/A	-	Provided by Client	-	-	-
Big Gear Modified	N/A	-	Provided by Client	-	-	-
Bondable Flex Circuit	N/A	-	Provided by Client	-	-	-
Bracket Bolt	N/A	-	Provided by Client	-	-	-
Cable Chain Interface	N/A	-	Provided by Client	-	-	-
Cable Crimp	N/A	-	Provided by Client	-	-	-
Clearance Cable	N/A	-	Provided by Client	-	-	-
Cover Bolt	N/A	-	Provided by Client	-	-	-
Cuff Locknut	N/A	-	Provided by Client	-	-	-
E-flite - EFLB910	53.29	N/A	Purchased	Prop Shop Hobbies	EFLB9106S30	Arrived
FSR Sensor	N/A	-	Provided by Client	-	-	-
Inner Link clamp	N/A	-	Provided by Client	-	-	-
M3 Nut	N/A	-	Provided by Client	-	-	-
Motor Cover Cable Clamp	N/A	-	Provided by Client	-	-	-
Motor Cover	Undetermined	7075 Aluminum Alloy - O (ss)	Manufactured	N/A	N/A	Undetermined
Maxon Motor	599.91	N/A	Purchased	Maxon	B7FFC8204F6C	4-6 weeks
Part:	Cost:	Materials:	Purchased or Manufactured:	Vender:	Part #:	Lead Time:
Outer Link clamp	N/A	-	Provided by Client	-	-	-
PCB Housing	518.5	PLA Carbon Fiber Filament	Manufactured	Markforged	F-FG-0005	Arrived
PCB	N/A	-	Provided by Client	-	-	-
Pogo Pin Connector	N/A	-	Provided by Client	-	-	-
Pulley w/ Washer	N/A	-	Provided by Client	-	-	-
Quick Connect Footplate	N/A	-	Provided by Client	-	-	-
Roller Chain	N/A	-	Provided by Client	-	-	-
Motor Motor - Upright	Undetermined	7075 Aluminum Alloy - O (ss)	Manufactured	N/A	N/A	Undetermined
Motor Mount - leaf	Undetermined	7075 Aluminum Alloy - O (ss)	Manufactured	N/A	N/A	Undetermined
STTR Upright	N/A	-	Provided by Client	-	-	-
Slider Spacer	N/A	-	Provided by Client	-	-	-
Small Motor Cover Cable Clamp	N/A	-	Provided by Client	-	-	-
Calf Cuff Adjuster	N/A	-	Provided by Client	-	-	-
Strain Gage	N/A	-	Provided by Client	-	-	-
Terminal Pads	N/A	-	Provided by Client	-	-	-
Motor O-ring	16.91	Fluorine Rubber	Purchased	Amazon	N/A	1 week
PCB Housing O-ring	16.9	Rubber	Purchased	Amazon	N/A	1 week
Torque Sensor Quick Connect	N/A	-	Provided by Client	-	-	-
M3 25mm w/ Bolt	N/A	-	Provided by Client	-	-	-
M5 12mm w/ Bolt	N/A	-	Provided by Client	-	-	-
Motor Bracket	Undetermined	7075 Aluminum Alloy - O (ss)	Manufactured	N/A	N/A	Undetermined
motor cap	254.97	PLA Carbon Fiber Filament	Manufactured	Markforged	F-MF-0001	Arrived
Cuff assembly	N/A	-	Provided by Client	-	-	-
All Other screws	N/A	-	Provided by Client	-	-	-

Table 5-C: Bill of Materials

6 Design Validation and Initial Prototyping

6.1 Failure Modes and Effects Analysis (FMEA)

Some of the biggest aspects of our project involve open wiring with no insulative properties or protection. Our job is to design parts for these assemblies that will withhold an outdoor environment. We are designing these parts with thermal management and ingress protection in mind.

Some of our critical potential failures could come from the protective covering of the motor and Battery/ PCB compartment. As of now we had designed an O-ring fitting for each compartment to insure a water type seal. If that seal was ever to be broken and water made its way into the motor or PCB then we could have damaged a component which would be a costly lesson to us. We design our parts with a tight tolerance to leave no gap for foreign material to enter the system and to reduce our chances of failure.

Another way we as a team must be cautious is when it comes to thermal management. The electrical components that we deal with have potential to get very hot during extreme stress which could damage the part or at least reduce the life of the part. So, in designing our protective covering we need to keep in mind how we will disperse the heat that these parts create while protecting the rest or the system. So far, our team has design parts with hope that we could use heat transfer through the protective material to disperse the heat. Using heat syncs and small DC fans we have situated on our conductive protective covering (Aluminum Alloy 7075 – O (ss)) we hope to transfer that heat coming from our electrical components.

Most of our parts are brackets and our only concern with the brackets are the possibility of the being too heavy for the user. The risk to trade off we have here is the balance between making them strong enough to hold up and light enough for the user to comfortably operate.

Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Potential Causes and Mechanisms of Failure	RPN	Recommended Action
Maxon Motor	Exessive force	Motor is less functional or broken	System is mishandled	200	Add more protection to cover
	Thermal deformeatipon	Motor can sieze	Improper termal management	30	Add more thermal management
	Abraisive wear	Motor is less functional or broken	Regular use	500	Add more protection to cover
	Corrosion from outside elements	Motor won't work with other components	Improper ingress protectiont	50	more ingress protection
Motor support	Exessive force	Motor could sag	Regular use	500	brace suppot
	Tempurature induced deforation	Support could break or become brittle	Used out in freezing weather	50	Add more thermal management
	Cycle fatigue	Support could wear	rubbing from cloths	200	Add more protection to cover
Motor ingress protection	Tempurature induced deforation	O-ring could go bad	extreme temperatures	300	different design
	Exessive force	Cover can fracture	System is mishandled	200	Add more protection to cover
	Thermal fatigue	Cover can become brittle	extreme temperatures	50	Add more thermal management
	Impact wear	Cover can fracture	Regular use	500	Add more protection to cover
PCP	Impact fracture	PCP can break	System is mishandled	200	Add more protection to cover
	Thermal fatigue	PCP can overheat	not enough thermal management	30	Add more thermal management
	Cycle fatigue	Small parts can wear	Regular use	500	different design
	Corrosion from outside elements	PCP can overheat or short circuit	left in weather for extended period	50	add more ingress protection

Battery	Cycle fatigue	Battery can loose power	Regular use	500	different design
	Tempurature induced deforation	Can compromise battery life	overloading the battery	300	Add more thermal management
	Corrosion from outside elements	Can kill the battery	water seeps in	30	add more ingress protection
	Stress Rupture	Can break protective seal	overloading the battery	50	different design
	Exessive force	Can break protective seal	System is mishandled	100	Add more protection to cover
PCP/ Battery ingress protection	Exessive force	Cover can fracture	System is mishandled	100	Add more protection to cover
	Tempurature induced deforation	O-ring could go bad	Improper termal management	300	different design
	Thermal fatigue	Cover can become brittle	extreme temperatures	50	Add more thermal management
	Impact wear	Cover can fracture	System is mishandled	100	Add more protection to cover
Themal management of PCP/ Battery	Adheisive wear	Loose effective dissipation	misclaculated shifting of parts	100	fix it's mounting
	Exessive force	Can brittle the material	System is mishandled	300	Add more protection to cover
	Corrosion from outside elements	Loose effective dissipation	water seeps in	50	add more ingress protection
	Cycle fatigue	Can brittle the material	Regular use	500	Add more thermal management
Themal management of Motor	Adheisive wear	Loose effective dissipation	misclaculated shifting of parts	100	fix it's mounting
	Exessive force	Can brittle the material	System is mishandled	300	Add more protection to cover
	Corrosion from outside elements	Loose effective dissipation	water seeps in	50	add more ingress protection
	Cycle fatigue	Can brittle the material	Regular use	500	Add more thermal management

Table 6-A: FMEA Chart

Our recommended actions consist of adding more protection or more thermal management properties, what we need to do as a team is find the balance point between making the Exo-Ankle bullet proof and light weight. The risk Trade-off for our recommended actions are to better brace the motor, PCP, Battery and cover which will be better accessed in testing of the Ankle-Exo.

6.2 Initial Prototyping

6.2.1 Physical Prototype

Due to the nature of our project, until receiving the final say from Dr Lerner to buy the new parts recently, we did not know the exact specifications of our re-designs. With a new motor, new battery, and a task to move the PCB to the leg, a partial re-design of the exoskeleton is necessary, the new motor requiring most of the drive system be rebuilt. Before we received the actual specifications, we only had the full CAD model of the existing exoskeleton and a general idea of the sizes and specifications of the new parts. Using the CAD model, we 3d printed a full-size model of the exoskeleton, sans the footplate and cuff, which are thin carbon fiber parts that were very difficult to print. The purpose of this first prototype was to create a way to analyze the model outside of the CAD. Because the actual exoskeleton cannot leave the biomechatronic lab, and the new parts had not been finalized at the time, this would be our only way to modify a real model for the time being. Because this prototype served only for design, we printed subassemblies together, meaning that the model could not be disassembled and reworked. We printed the model using Nicks printer, which ran into several issues through the process. First, the nozzle jammed, and replacements had to be purchased. Then the thermistor which monitors the extrusion temperature died, and the heating block was replaced. Lastly, the printer motherboard shorted and could not connect to the print server, needing to be replaced as well. The printer began running again close to the deadline, so several parts were fast, low-quality prints.

We are in the process of printing a new prototype, this time printing each part individually, so that we can rebuild the model for alternate designs. In the first prototype, some parts cracked from the screws as well as stress from the inaccurate tolerances from low-quality parts. In addition to adding tolerances to the part models, we will be using PLA carbon fiber filament rather than PLA, due to its high strength.

6.2.2 Virtual Prototype

Our working CAD model includes mounts for both the PCB and battery, and a new motor housing designed to protect the motor from moisture, debris and damage. Most of the drive system and some of the frame has been re-designed, including the full motor subassembly, the motor mount, and the front cover. The motor has an open back, leaving the coils exposed. Because of this, the motor housing prioritizes protection over heat diffusion, enclosing the entire motor and using an O-ring to seal the cover to the mount. As part of our virtual prototype, we conducted a heat transfer analysis on the motor and housing.

6.3 Other Engineering Calculations

6.3.1 Thermal Analysis – Alex Schell: We performed a thermal analysis on the motor. One of the main challenges our team faces is preventing heat from the motor from being felt by the user via the dispersal of the heat using a motor cover. This can happen either from the material used, or by the usage of heat sinks or a fan. Our current design puts some heat sinks around the perimeter of the cover, using aluminum as the material. While we are looking at a possible redesign on the current location of the heat sinks, the current thermal analysis is done on the current design.

The main equation used was to determine heat emanating from the coils in the motor. To solve for this, we used the formula for heat dissipation ($H_{dissipated}$)(1).

$$(1)\ \ H_{dissipated} = P_{input} * (1 - efficiency)$$

Input power, P_{input}, is the next calculation that needs to be completed. Formula (2) shows that this calculation is based on output power (P_{output}) and efficiency.

$$(2)\ \ P_{input} = \frac{P_{output}}{efficiency}$$

Efficiency was calculated by Ryan Oppel in section 3.3.3, assuming that it is 82.7%. As for output power, formula (3) demonstrates that it is based torque (T), and angular velocity (ω).

$$(3)\ \ P_{output} = T * \omega$$

$$(4)\ \ \omega = \frac{2\pi * RPM}{60}$$

Working with the assumption that the motor is working at nominal speed, of 184.3 rpm, angular velocity equals 19.30 rad/sec, allowing power output (P_{output}) to be 54.04 W. From here, we calculated input power(P_{input}) to be 65.34 W and dissipated heat ($H_{dissipated}$) to be 11.3 W. From here, we had to calculate the convective heat transfer coefficient to completer the thermal analysis in Solidworks. Convective heat transfer coefficient, formula (5), uses Nusselt number, and the thermal conductivity of air at 25 °C.

$$(5)\ \ h = \frac{Nu * k_{air}}{L}$$

Given that the structure is cylindrical, we used formula (6). [17] This formula uses Reynolds number (Re), which is calculated in formula (7) to be 18,598. Because this is less than 500,000, we can confirm that this flow is laminar.

$$(6)\ \ Nu = 0.3 + \frac{0.62 Pr^{1/3}}{\left[1 + (0.4/Pr)^{2/3}\right]^{1/4}} Re^{1/2} \left[1 + (Re/282000)^{5/8}\right]^{4/5}$$

$$(7)\ \ Re = \frac{\rho * u * L}{\mu}$$

For this formula, I assumed the following values: density (ρ) is 1.18 $\frac{kg}{m^3}$, flow velocity (u) is 5 m/s, dynamic viscosity (μ) is 1.64E-5 $\frac{kg}{m*s}$, thermal conductivity (k) is 0.026 $\frac{W}{m*K}$, and again, the Prandtl number (Pr) is 0.715. [18] Using these values, I calculate Nusselt number (Nu) to be 86.08. Now that we have Nusselt number, we can calculate the convective heat transfer coefficient (h) to be 38.59 $\frac{W}{m^2K}$.

6.3.2 Thermal Analysis – Alex Schell: Using the values calculated in 6.3.1, the team performed a thermal analysis on the current design in SolidWorks using SolidWorks Simulations. Figure 23 show the heat distribution across the motor. As shown, the heat is still high on the edge of the motor closest to the coils in the motor. The current design also has lower comfortability due to the spikes. This prompted the team to do a redesign on the location of the heat sinks.

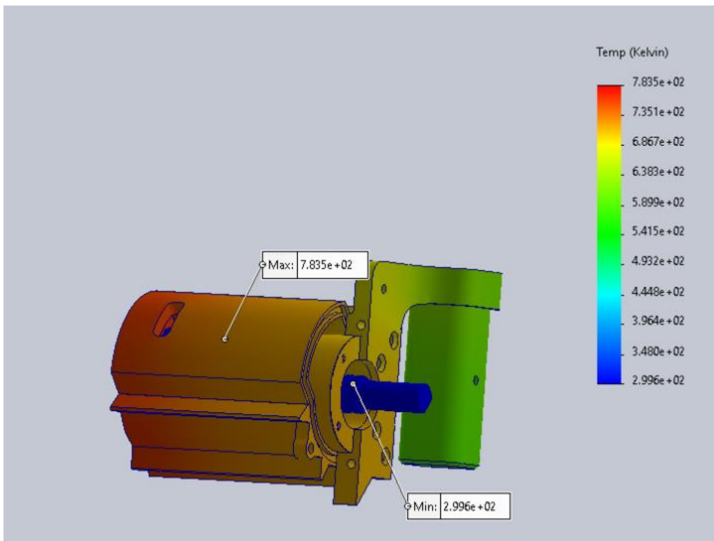


Figure 23: Thermal Analysis of motor cover

[Summarize all engineering calculations performed since the concept selection phase.]

6.4 Future Testing Potential

The first new part we need to install is the motor. Because the new motor has a higher torque than the old one, the effect of torque on the drive system, specifically the cable and crimps can be analyzed to verify that the increase in strain in not significant. The battery and PCB need to be moved from a belt onto the exoskeleton itself, enclosed in a protective cover. The main issue that this can cause is the heat produced from these parts. Batteries and PCBs both have a risk of overheating, so a thermal analysis could be done to determine if these parts require a cooling system. It is important that the exoskeleton remains lightweight after the new parts are installed, as the target users are individuals with muscular deficiencies, and a system that is too heavy will not allow the user to walk for long periods of time, if at all. Alternate materials for various parts of the exoskeleton can be researched, and the total and center of mass can be analyzed to decide if the weight of the new parts will make this necessary. Lastly, the heat transfer analysis was performed on the motor within the new cover, and if it is determined that the cover is not adequately diffusing heat then further steps could be taken. Either a cooling system could be built into the housing, or heat sinks could be either installed or built into the cover. If this is to be done, heat transfer analysis could be performed on different heat sink configurations, and calculations can be made to determine the thermal resistance and heat diffusion of different fin sizes.

7 CONCLUSIONS

For our capstone project, our team was tasked with improving a previous design for a below-the-knee Ankle Exoskeleton, developed by a past capstone team in collaboration with our client, Dr. Zachary Lerner of the NAU Biomechatronic Lab. The original exoskeleton was designed to aid people with walking impairments by enhancing ankle movement through a motor housed in the boot. In this design, the battery and microcontroller were positioned on a waist belt connected by wires running up the user's leg.

Our primary objective is to redesign the system to integrate all components below the knee, eliminating the need for the waist belt. To achieve these goals, several critical requirements needed to be met:

- The redesigned exoskeleton must not restrict the user's range of motion.
- The system must be lightweight to avoid user fatigue.
- The electrical components must have proper ingress protection to safeguard against debris and water.
- The system must pass stress and thermal testing to ensure comfort and safety for the user during extended use.

Thus far, we have worked on several key design aspects. We selected the Maxon ECX flat 32L motor, known for its stable torque output, paired with a Cell E-Flite battery to power the new system. Our new frame design ideas integrate all components behind the calf muscle, offering a more compact and ergonomic configuration. This frame includes paneling to house the battery and microcontroller, while maintaining user comfort and mobility.

In summary, the proposed solution features a re-engineered frame to accommodate the new components below the knee, updated motor and battery selections, and protective casing to ensure system durability in real-world conditions. This report details our design choices, calculations, and analysis that led to this solution, laying the foundation for testing and further refinement of the exoskeleton system.

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9 APPENDICES

9.1 Appendix A: Figure Models

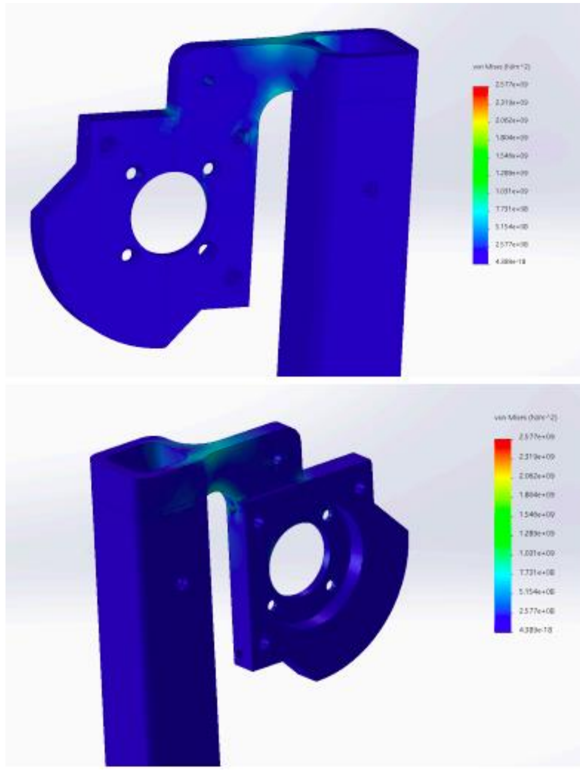

Figure 4-5: visuals of the FEA applied to the motor mounts with known variables

This FEA analysis shows us our weak points within the design. We can use this new information to helps us determine what we as a team need to do to better strengthen our design.

Figure 17: Assembly of our first prototype

Figure 17 is our completed assembly with the PCB/ Battery compartment mounted on to the Spark Plug Exo-skeleton design.

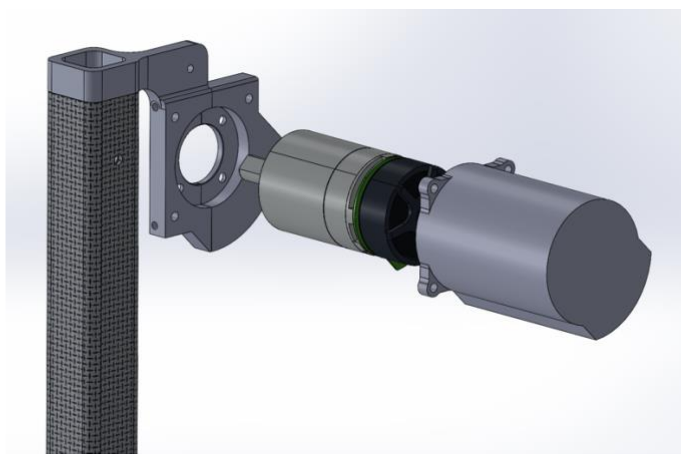

Figure 18: Assembly of our motor mount and protective covering

Figure 18 is our assembly with the aluminum cover over the new motor. This cover is supposed to protected the motor from impact, abrasion, foreign material, and thermally protect it as well. A heat sync will be mounted onto the flat end of the cover with a small DC fan.

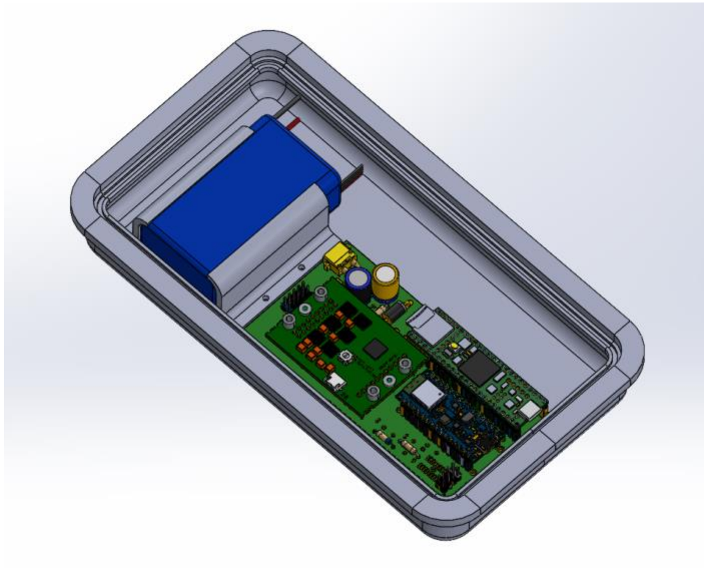

Figure 19: Assembly of our Battery/ PCB Protective Covering

Figure 19 is our PCB/ Battery Compartment. This is to show just how each piece will fit into the compartment and give room for the wires that will be running through here and to the battery.

9.2 Appendix B: Table/Equation Models

Part:	Cost:	Materials:	Purchased or Manufactur	Vender:	Part #:	Lead Time:
8mm Steel Ball Bearing	N/A	-	Provided by Client	-	-	-
Medium-Strength Steel Nylon	N/A	-	Provided by Client	-	-	-
Stainless Steel Button Head Torque Screws	N/A	-	Provided by Client	-	-	-
Alloy Steel Socket Head Screw	N/A	-	Provided by Client	-	-	-
Big Gear Modified	N/A	-	Provided by Client	-	-	-
Bondable Flex Circuit	N/A	-	Provided by Client	-	-	-
Bracket Bolt	N/A	-	Provided by Client	-	-	-
Cable Chain Interface	N/A	-	Provided by Client	-	-	-
Cable Crimp	N/A	-	Provided by Client	-	-	-
Clearance Cable	N/A	-	Provided by Client	-	-	-
Cover Bolt	N/A	-	Provided by Client	-	-	-
Cuff Locknut	N/A	-	Provided by Client	-	-	-
E-flite - EFLB910	53.29	N/A	Purchased	Prop Shop Hobbies	EFLB9106S30	Arrived
FSR Sensor	N/A	-	Provided by Client	-	-	-
Inner Link clamp	N/A	-	Provided by Client	-	-	-
M3 Nut	N/A	-	Provided by Client	-	-	-
Motor Cover Cable Clamp	N/A	-	Provided by Client	-	-	-
Motor Cover	Undetermined	7075 Aluminum Alloy - O (ss)	Manufactured	N/A	N/A	Undetermined
Maxon Motor	599.91	N/A	Purchased	Maxon	B7FFC8204F6C	4-6 weeks
Part:	Cost:	Materials:	Purchased or Manufactured:	Vender:	Part #:	Lead Time:
Outer Link clamp	N/A	-	Provided by Client	-	-	-
PCB Housing	518.5	PLA Carbon Fiber Filament	Manufactured	Markforged	F-FG-0005	Arrived
PCB	N/A	-	Provided by Client	-	-	-
Pogo Pin Connector	N/A	-	Provided by Client	-	-	-
Pulley w/ Washer	N/A	-	Provided by Client	-	-	-
Quick Connect Footplate	N/A	-	Provided by Client	-	-	-
Roller Chain	N/A	-	Provided by Client	-	-	-
Motor Motor - Upright	Undetermined	7075 Aluminum Alloy - O (ss)	Manufactured	N/A	N/A	Undetermined
Motor Mount - leaf	Undetermined	7075 Aluminum Alloy - O (ss)	Manufactured	N/A	N/A	Undetermined
STTR Upright	N/A	-	Provided by Client	-	-	-
Slider Spacer	N/A	-	Provided by Client	-	-	-
Small Motor Cover Cable Clamp	N/A	-	Provided by Client	-	-	-
Calf Cuff Adjuster	N/A	-	Provided by Client	-	-	-
Strain Gage	N/A	-	Provided by Client	-	-	-
Terminal Pads	N/A	-	Provided by Client	-	-	-
Motor O-ring	16.91	Fluorine Rubber	Purchased	Amazon	N/A	1 week
PCB Housing O-ring	16.9	Rubber	Purchased	Amazon	N/A	1 week
Torque Sensor Quick Connect	N/A	-	Provided by Client	-	-	-
M3 25mm w/ Bolt	N/A	-	Provided by Client	-	-	-
M5 12mm w/ Bolt	N/A	-	Provided by Client	-	-	-
Motor Bracket	Undetermined	7075 Aluminum Alloy - O (ss)	Manufactured	N/A	N/A	Undetermined
motor cap	254.97	PLA Carbon Fiber Filament	Manufactured	Markforged	F-MF-0001	Arrived
Cuff assembly	N/A	-	Provided by Client	-	-	-
All Other screws	N/A	-	Provided by Client	-	-	-

Table 5-C: Bill of Materials

Since our project is operating on a previous design, we are being provided most of these parts. We decided to add them because even though we do not plan on buying these parts, they are still going to be a part of our final build.