Below-the-Knee Exoskeleton

Initial Design Report

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NORTHERN ARIZONA UNIVERSITY

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DISCLAIMER

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EXECUTIVE SUMMARY

For our team's capstone project, we are tasked to improve upon a previous capstone 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 of 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 so as to not reduce the effectiveness of the exoskeleton.

The entirety of our design contributions will include a new frame that will harness to the user, protective covering for the electrical components, and overall, a different configuration to the components on the frame.

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. CAD models for our new design 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 is 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 of 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 impairment. According to our sponsor, 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. Finally, we are to create a new cover and ingress protection design.

For the purpose of 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 $175.

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 to select an optimal motor and battery selection and configuration. This analysis considers factors such as power requirements, efficiency, weight, and compatibility with the system's operational demands.
3. **Motor 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.
4. **Cover and Ingress Protection Design:** The cover design focuses on safeguarding internal components while providing ingress protection (IP rating) against dust 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. The following table breaks down the success matrix.

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.	Weeks 1-3
Motor Mount	Develop a durable, lightweight motor mount that securely	Success is determined by CAD designs, stress analysis (FEA), and testing for vibration	Weeks

Design	houses the motor below the knee, without adding excessive weight or hindering movement.	resistance. There should only be one reference list in this report, so all individual section or subsection reference lists must be compiled here with the main report references.	5-9
Cover and Ingress Protection Design	Design a cover that provides protection for the motor and electronics, ensuring no environmental ingress (dust, 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 a specified duration 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.

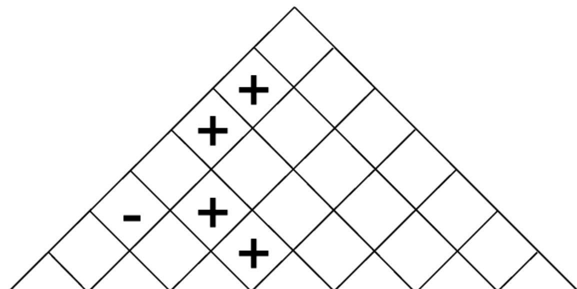
2.1 Customer Requirements (CRs)

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. Because of this, the system will likely be used for an entire day at a time, thus both comfort and a long battery life, both of which can sustain the user for a full day are relevant to the product. 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 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)

A lightweight design is our most important design requirement, and based on other similar products, 3kg is the maximum weight that the system should total. A device that is too heavy will be impossible for certain users with more severe conditions, which is unacceptable as those individuals are the most in need of the product. Ability to accommodate users of all weights as well as different foot sizes are significant as, once again, the device is intended for all users with conditions that require the assistance that this device can provide. High torque is related closely with the accommodation of users of all weights. The device is intended to assist users rather than fully support them, however a motor with a higher torque will provide aid to users with more severe conditions who require the extra assistance. The temperature of the motor is an important requirement, and will be further discussed in Concept Selection, but the motor, depending on placement, can transfer heat to the battery and the user's leg, which could possibly cause the battery to overheat, or burn the user's skin. A low production cost will be necessary once this device is intended for general use, however as the design is still a functional prototype and only used within the lab, we are unable to determine a target for this requirement. Energy efficiency is the lowest rated requirement, because the current design can operate for about four hours, and selecting a new battery and motor are some of our current tasks.

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	Low production cost	1 Worst	2	3	4	5 Best
Durable	3		3		6	6	6			C	AB		
High range of motion	5			9							B	AC	
Comfortable	4		3		3							A	
High battery life	3	9					9					B	
Adjustable	3		3		6							C	A
Lightweight	5					9						B	AC
Affordability	5							9		C	B		
Technical Importance: Absolute		27	30	45	48	63	45	45					
Technical Importance: Relative		9%	10%	15%	16%	21%	15%	15%					

Improvement Direction; Customer Competitive Assessment:

A	Caplex Exo
B	Utah Knee
C	ETM Motor

		Energy efficient	Accommodate different shoe sizes	High torque	Support users of all weights	Under 3 kg	Temperature of motor	Low production cost
Design Competitive Assessment	**Worst: 1**							B
	2				C		B	C
	3	AB		B		C	C	
	4			C	A	B		
	Best: 5	C	A	A		A		
Target Value		4	0.3	70	90	2	35	
USL		8	0.27	140	120	3	70	
LSL		2	0.22	20	30	1.5		
Units		hr	m	Nm	kg	kg	C	

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

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

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

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

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

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

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

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 Alex Schell: Kinematics and Kinetics of the Foot and Ankle during Gait [8]

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.

3.2.9 Alex Schell: Cadaveric Gait Simulation [9]

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.

3.2.10 Alex Schell: Developments and clinical evaluations of robotic exoskeleton technology for human upper-limb rehabilitation [10]

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.

3.2.11 Alex Schell: Toward High-Performance Lithium–Sulfur Batteries: Efficient Anchoring and Catalytic Conversion of Polysulfides Using P-Doped Carbon Foam [11]

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.

3.2.12 Alex Schell: A Lightweight, Efficient Fully Powered Knee Prosthesis with Actively Variable Transmission [12]

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.

3.2.13 Alex Schell: F3527 Standard Guide for Assessing Risks Related to Implementation of Exoskeletons in Task-Specific Environments [13]

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.

3.2.14 Alex Schell: The Essential Guide to Selecting Batteries for Robotics [14]

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.

3.2.15 Alex Schell: Batteries for Electric Vehicles [16]

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.

3.2.16 Nick Watkins: Prosthetic forefoot and heel stiffness across consecutive foot stiffness categories and sizes [17]

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.

3.2.16 Nick Watkins: Robotic Emulation of Candidate Foot Designs May Enable Efficient, Evidence-Based, and Individualized Prescriptions [18]

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.

3.2.16 Nick Watkins: F3528-21 Standard Test Method for Exoskeleton Use: Gait [19]

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.

3.2.16 Nick Watkins: G-Exos: A wearable gait exoskeleton for walk assistance [20]

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

3.2.16 Nick Watkins: The Mechanical Functionality of the EXO-L Ankle Brace [21]

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

3.2.16 Nick Watkins: Pilot evaluation of changes in motor control after wearable robotic resistance training in children with cerebral palsy [22]

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.

3.2.16 Nick Watkins: Does Ankle Exoskeleton Assistance Impair Stability During Walking in Individuals with Cerebral Palsy? [23]

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.

3.3 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.

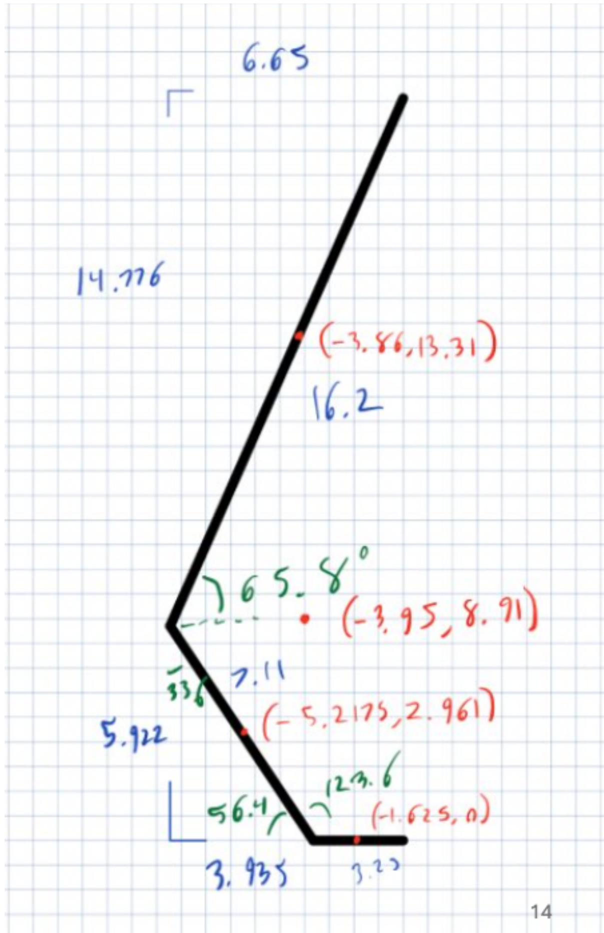


Figure 2: Center of Mass

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.

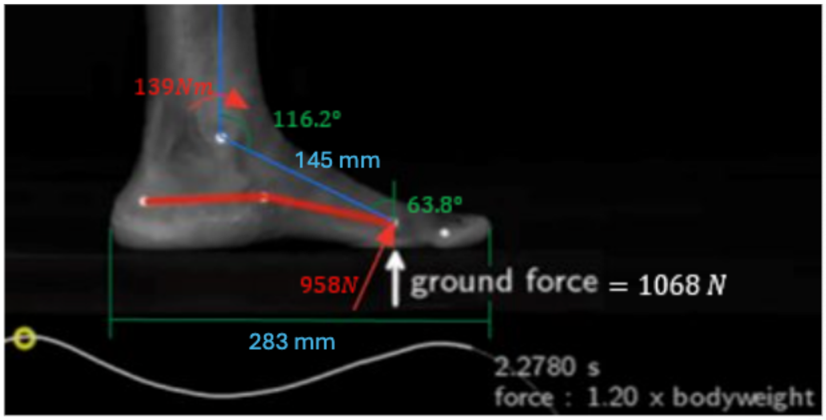


Figure 3: Free Body Diagram

(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

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

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

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

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

Figure 4: Mathematical Modeling Calculations

3.3.3 Torque Output by Motor – Ryan Oppel: Since we are building upon the previous model it's important to know how much torque the original motor could apply to the previous design. Figure 5 shows the exploded view of the motor. Reading through the research paper of the previous design we find that they used a 90 W Maxon motor with an 89:1 gearbox. The torque input from the motor is only 43.7 mNm. That is hooked up to a gear box with a ratio of 89:1 means that the torque output is approximately 3.7 Nm of force. This is done using the formula for Torque Output in figure 6. The specs of the motor give an efficiency Rating of 88% at nominal voltage. While giving the gearbox a rough estimate of an efficiency rating of 94%. We calculate that the overall efficiency rating of the system is 82.7%. Figure 7 demonstrates the formulas used to calculate the overall Efficiency rating. The previous system had an output torque of 3.7 Nm with an efficiency rating of 82.7%.

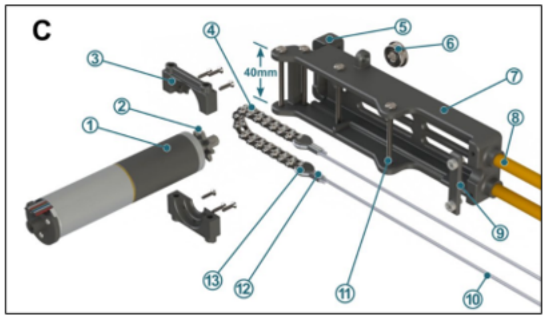


Figure 5: Exploded View of Motor

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

Figure 6: 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:

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

Figure 7: 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 figure 8 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

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

τ = Stress

T = Torque

r = radius of the shaft

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

Figure: 8 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 9 demonstrates the Von Mises stresses based on a force of 15N. Figure 10 demonstrates Life Cycle based on 15N after 1000000 cycles.

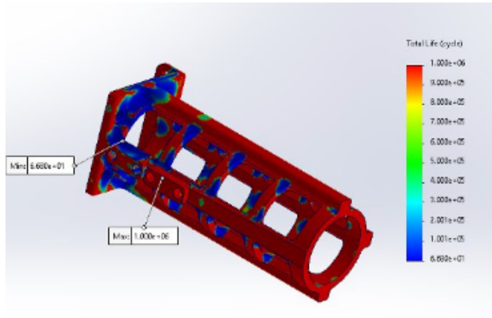


Figure 9: Von Mises Stress

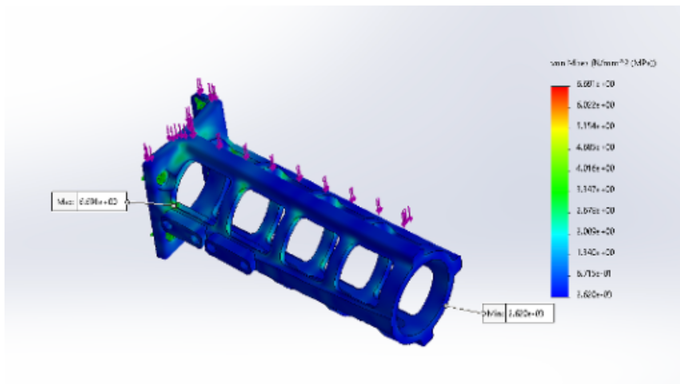


Figure 10: Life Cycle

4 Design Concepts

4.1 Functional Decomposition

Figure 11 depicts the physical 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 standard and successful with the overall design.

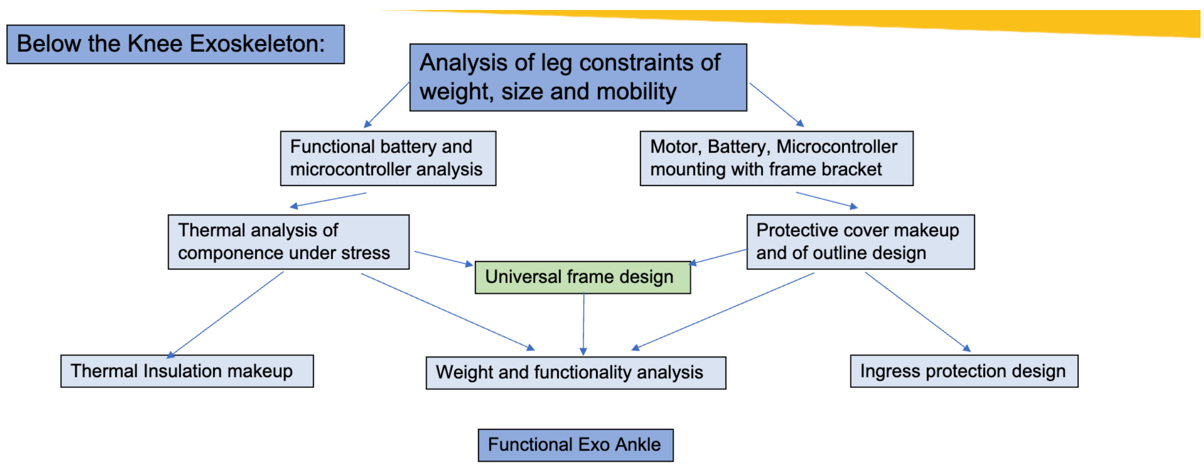
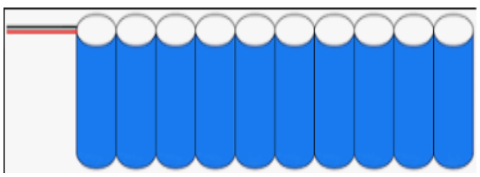


Figure 11: Physical Decomposition

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 12: 3500mAh 10A Protected Lithium Ion*	 *Figure 13: Dantona L148A26-4-18-3WA3 Lithium-Ion Battery Pack*
 *Figure 12: Li-Ion 21700 Battery*	 *Figure 13: 2p3s 10.8v 6400Mah Lithium Battery Pack*

Because the battery still needs to be selected, the batteries in the following designs are conceptual regarding shape and size. The 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.

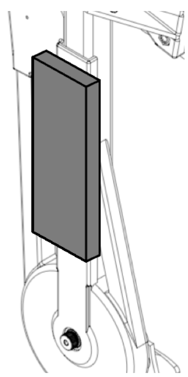


Figure 14: Battery mounted on the frame

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.

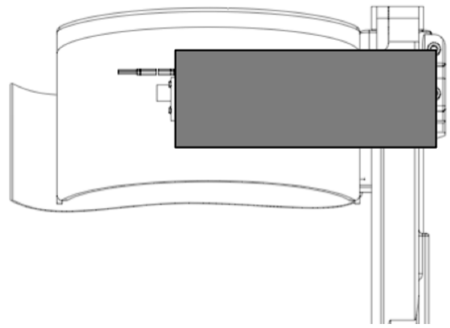


Figure 15: Battery mounted on the motor

Figure 18 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.

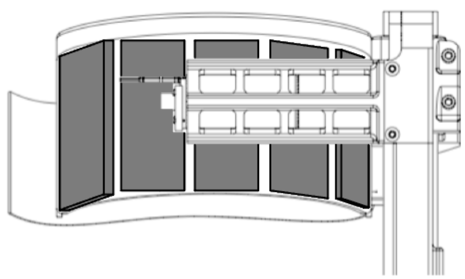


Figure 16: Battery cells mounted on the cuff

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.

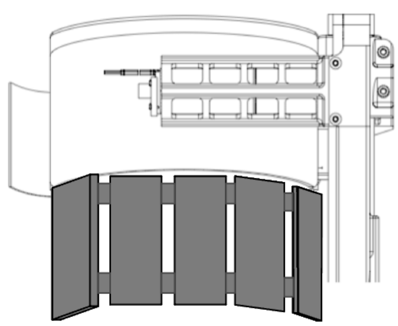


Figure 17: Battery cells mounted under the cuff

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.

First off, the Motor. 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 20: Factory Specifications of old motor without gearbox

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 21: Factory Specifications of new motor without gearbox

As we can see through the specifications of each motor, 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.

Next is our battery, our battery criteria had four different parts to them; output power, weight and size, ease of use, cost. Because we plan to do a cell battery configuration, we can string as many batteries as we need to operate the Exoskeleton. Meaning the most important criteria to us is the wieght and size of the battery. The categories we looked at in a battery were the voltage, amperage, and amperage per hour all based on weight and size. We looked at 4 different types of battery configurations with different cells and we concluded that by wieght, the most powerful battery we found for the smallest amount of weight is the 2p3s 10.8v 6400Mah Lithium Battery Pack as shown in figure 5. However, after talking with our client (Prof. Lerner) he decided on a battery cell for us to use. This new battery, why more geometrically complicated for us, has a much higher voltage output than our previous design which means we do not have to make as many cells of the battery.

Lastly our frame configuration. 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 9. 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

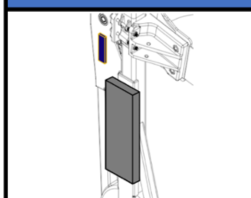
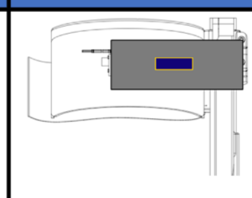
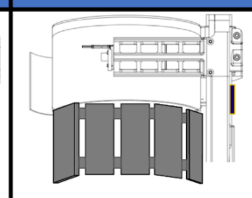
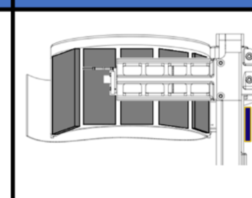
		1	2	3	4
					
High Center of Gravity	1	-	+	S	+
Heat Transfer to Skin	3	+	+	-	S
Heat Transfer to Electronics	4	+	-	+	-
Protection	5	-	-	+	+
Σ		1	-5	6	2

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 a number of 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.

5 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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7 APPENDICES

7.1 Appendix A: Design Concepts

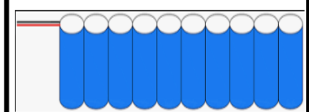
		1	2	3	4
		3500mAh 10A Protected Lithium Ion 	Dantona L148A26-4-18-3WA3 Lithium-Ion Battery Pack 	Li-Ion 21700 Battery 	2p3s 10.8v 6400Mah Lithium Battery Pack 
Output power	2	S	-	+	+
Weight and size	3	-	+	-	S
Ease of use	2	+	+	-	+
cost	2	+	-	+	-
TotalΣ		1	1	-1	2

Table A 1: Battery selection decision matrix

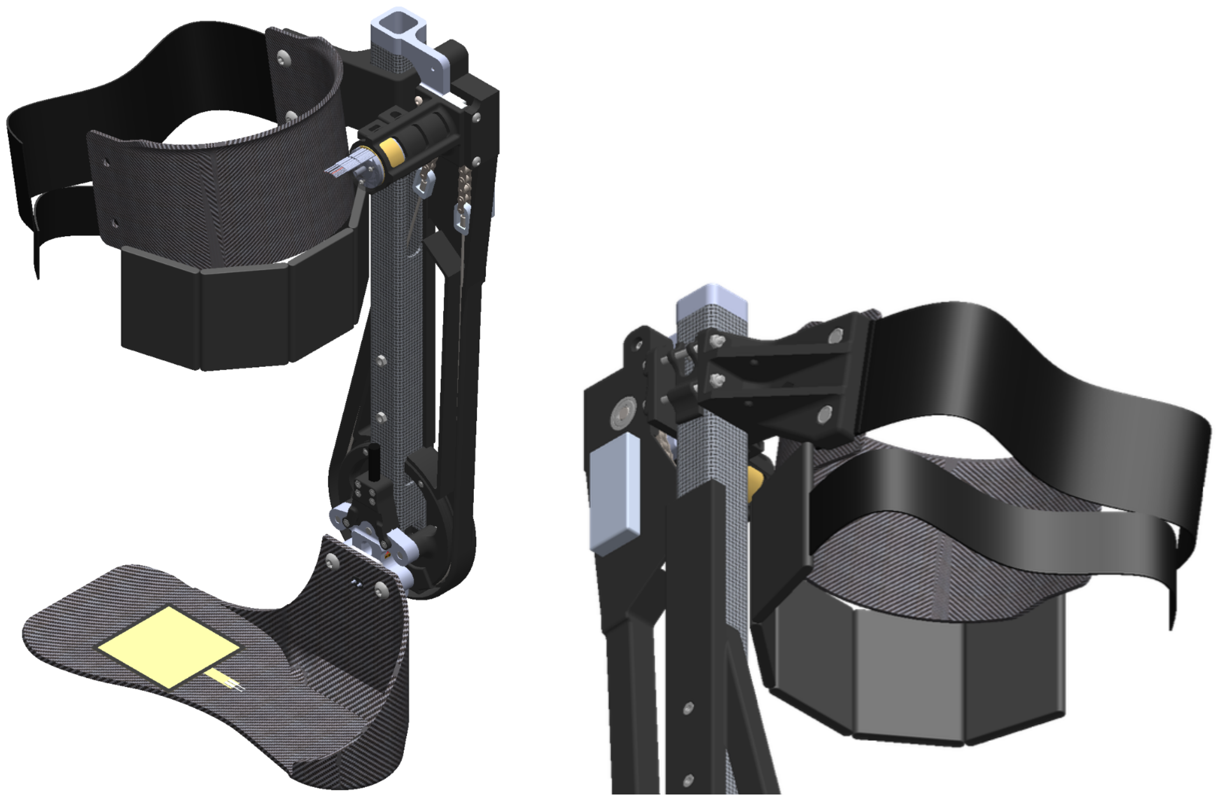


Table A 2: Isometric CAD drawings of the design with updated motor and battery & Arduino placement