Robotic Ankle Exoskeleton

Initial Design Report

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EXECUTIVE SUMMARY

This report goes through the beginning process of creating a Robotic Ankle Exoskeleton. This project is focused on reiterating portions of a previous design created during the 2021-2022 academic year with help from the NAU Biomechatronics lab. Our team is specifically focusing on the chain system and overall bracket design. The design change includes changing from a sprocket to gear pulley to a sprocket to cable pulley and updating the bracket design to improve the overall strength of the design. To the date the team has designed the new bracket design and completed calculations to determine the best design to prototype moving forward. The calculations specifically made include determining the force that will act on the skeleton design, the forces on the attachment point, the torque acting on the ankle, tension within the cable on the cable pulley, the thickness of the footplate, and forces acting on the various bracket designs. The team has determined the bracket design to prototype moving forward from the calculations completed. The report goes into specific details for each portion mentioned above.

TABLE OF CONTENTS

Contents

1 BACKGROUND

The following section covers the general description of the defined project and the approach taken to solve the engineering problem. By building on previous iterations, this team has developed a new approach to improve aspects of previous designs. The ultimate goal is to improve the walking gait of people who have cerebral palsy and decrease the amount of biomechanical torque that their body has to produce at the ankle through mechanical assistance. The overview of completed deliverables and the expected steps going forward are stated in the following subsections, including the budget and future goals for fundraising.

1.1 Project Description

We partnered with Professor Zachary Lerner at NAU's Biomechatronics lab to develop an ankle exoskeleton to aid the walking motion and help improve the mobility of our clients with Cerebral Palsy. Our focus is primarily on the physical structure of the design, and not so much on the motor or sensor inputs. The previous trial "did not observe a significant group-level benefit relative to walking without the device. However, [they] did observe a marked benefit for [their] more impaired participants" [1] We intend to reiterate parts of their design, such as the bracket and pulley system. However, we are integrating a cable to chain system to avoid slippage. Through our development and cooperation with Doctor Lerner, we have calculated the gear ratios, bracket design, and are now working on a CAD model. The entirety of our project needs to remain under $4,000, including all testing and prototypes. In addition, the team has to raise $400.00 in additional funds for the project.

1.2 Deliverables

The deliverables completed so far have been calculations based on:

-Torque experienced by the Achilles Tendon

-Gear ratios and force output

-Material Selection

-Geometry of bracket (last one sheared)

-Cross sections of members

-Type of fasteners

-Cable Tension

Each of these deliverables validates our approach to answering our engineering problem and provides metrics to use in comparing methods/designs. The deliverables that need to be completed moving forward are developing a CAD model of our recommended design, 3D printing a model, and then completing a functional prototype. Each member of the team will then choose an aspect of the design to analysis and justify/explain its validity in a report memo.

1.3 Success Metrics

Most design metrics for this project are not going to be based on pass/fail, but whether it improves the walking gait. Our design is expected to go through the same tests that the previous group did, including:

-Assembly time

-Weight Requirements

-Time to take on/off

-Torque Output

-Performance

-Terrain accessibility

-Client feedback

As a conclusion to the project, we will be expected to monitor a client as they test our design and analyze the output feedback that we receive from the motor and pressure plate sensors. This will be the most important test as it validates our design or gives crucial feedback on what needs to be improved upon in the next iteration.

2 REQUIREMENTS

This section will discuss the requirements that were given to us by our customer regarding what he wants to see in our final product. Using these customer requirements, we then quantified these requirements to give us engineering requirements. Which gives us quantifiable values which our product needs to meet to be able to be considered a success. Then using these two requirements we then created a house of quality, which will explain the correlation between the customer requirements and the engineering requirements. Then the house of quality also shows the weight of each requirement. These weights show how important each requirement is to the customer. Using this house of quality will allow us to create an effective design that will meet each criterion, while also allowing us to prioritize certain requirements over others.

2.1 Customer Requirements (CRs)

During our client meetings with Lerner, we discussed some of his requirements which he would like us to accomplish in our product. These customer requirements are listed below.

1. Lightweight
2. Easly put on and taken off
3. Durable
4. Economical
5. Low profile
6. Have a chain to pulley system

The first customer requirement that we were given is that the ankle exoskeleton needs to be lightweight. This is because the users of this product will be teens and children with cerebral palsy, so having a heavy exoskeleton will be very advantageous for the user. The second requirement is that it needs to be easily taken on and off. This is to allow for the user to easily put on and remove the product. The third requirement is it needs to be durable. Meaning that our design needs to be able to last for multiple uses. The fourth requirement is that our product needs to be cost effective. So, we need to keep our costs for the product as low as possible without compromising on the quality. The second to last requirement is that our design needs to be low profile and agronomical. So that our product doesn't unnecessarily protrude from the ankle or cause a hinderance to the user during their daily life. The last customer requirement is that the actuating system for our exoskeleton must use a chain to pulley system.

2.2 Engineering Requirements (ERs)

The following deliverables are our constraints moving forward:

-$4,000.00 budget

-Range of motion should be 45 degrees in either direction (resting is 90)

-Weight < 1 kg per leg

-Cannot extrude from the body more than 10 cm

-Lifetime of 100,000 steps

-Time to take on/off (<60 s)

There is a lot of creative room for the engineers on this project. Considering that biomechanics is a newer advancement, there are not many designs to reference. Because of this, we are working off of the previous team's progress and fixing aspects of that design. Through trial and error, Doctor Lerner has directed us to reposition the motor house onto the calf cuff and feed our pulley cables through the supporting bracket. This requirement doesn't necessarily have a quantitative result, but it is a requirement for our design.

2.3 House of Quality (HoQ)

After discussing the engineering requirements and customer requirements, a House of Quality (Figure 1) was created. A House of Quality is a visual way to see the correlation between the engineering requirements and customer requirements and is used to see how the team can improve the teams design to make it better than those already on the market.

Within the House of Quality, it includes the customer requirements and the weights of each requirement. This includes lightweight, easy to take on and off, durable, cost effective, and small in size or close to body. The team then weighted each requirement in terms of importance. The most important requirement was that it was cost effective to make, this is to ensure that the exoskeleton can be replicated for a cheap cost making it more accessible to the population. The second requirements include easy to take on and off and durable. This is to ensure our design can be put on and off by the user without assistance from a researcher or designer and that is lasts long enough for the device to be helpful. Lastly, lightweight and small in size were the least important, as if the design is slightly heavier or larger in size it might not be as big of an issue as the other requirements.

The customer requirements were then transformed into quantitative engineering requirements. Which include decreasing the weight, increasing the durability, decreasing the timing, decreasing the cost of each leg, and decreasing the protrusion from the body. Each requirement has a quantitative value attached to it, those are: each leg being less than 1kg, each leg lasting at least 100,000 steps, it taking less than one minute to take on and off, each leg being less than $2,000, and each leg being less than 10cm from the body.

Each engineering requirement was then compared to each customer requirement stating whether it has a strong positive correlation (++), a positive correlation (+), a neutral (0), a negative correlation (-), or a strong negative correlation (--). Positive correlation means that if one requirement changes the other will also change in a positive way. Negative correlation means that if one requirement changes the other will change in a negative way. A neutral correlation implies that if one changes the other won't change or it won't change in a positive or negative way. The team found that decreasing the protrusion from the body strongly positively correlates with decreasing weight. Decreasing the cost of each leg positively correlates to decreasing weight and decreasing the time it takes to remove the exoskeletons. Decreasing timing has a neutral correlation with decreasing weight. Decreasing the protrusion has a neutral correlation to increasing durability, decreasing timing, and decreasing the cost of each leg. Lastly, there was a negative durability between increasing durability and decreasing weight, as well as, increasing durability and decreasing the cost of each leg and decreasing timing.

After comparing each requirement, they are then compared to three different devices within the industry currently. Those are the Technaid Eobotic Ankle H3, Rewalk Restore Soft Robotic Exoskeleton, and the Untelthered Robotic Ankle Exoskeleton. Each specific design is explained in the benchmarking section. The team then ranked each design based on how we felt it stood up to the customer requirements. Finding that each design has excellent features, acceptable features, and poor features.

A	Technaid Eobotic Ankle H3
B	Rewalk Restore Soft robotic Exos
C	Untelthered Robotic Ankle Exos

		1	2	3	4
1	Decrease Weight				
2	Increase Durability	-			
3	Decrease Timing	0	-		
4	Decrease Cost of Each Leg	+	-	+	
5	Decrease Protrusion From Body	++	0	0	0

	Customer Needs	Customer Weights	Decrease Weight	Increase Durability	Descrease Timing	Decrease Cost of Each Leg	Decrease Protrusion from Body	1 Poor	2	3 Acceptable	4	5 Excellent
1	Lightweight	3	5	3	3	3	3	A				BC
2	Easy to take on and off	4	3	1	5	3	3		BC		A	
3	Durable	4	2	5	1	2	1			ABC		
4	Cost Effective	5	4	4	1	5	1					
5	Small in size, close to body	3	5	2	3	2	5	A	B		C	
	Technical Requirement Units		kg	steps	min	dollars	cm					
	Technical Requirement Targets		<1	100,000	<1	<2000	<10					
	Absolute Technical Importance		19	15	13	15	13					
	Relative Technical Importance		1	2	3	2	3					

Figure 1: House of Quality

3 Research Within Your Design Space

3.1 Benchmarking

For our benchmarking we decided to look at 4 different robotic exoskeletons to assist us during our concept generation. Each of these products are not made for the same disorders, but each has something unique to offer during our concept generation. These products will be explained in greater detail in the following paragraphs.

The first product that will be looked at is the previous capstone project, which is shown below in Figure 2. It is extremely important for us to evaluate the previous capstone to try to learn from their mistakes. While also finding what they did right and trying to duplicate those things. Such as with their chain system and their carbon fiber rod design. But also improving their bracket design and how the bracket attaches to the carbon fiber rod, since this is where their design failed. So, using their design for benchmarking will greatly help us through our project life cycle.

Figure 2: Fully Active Chain and Sprocket Ankle Exoskeleton for Rehabilitation Assistance

The next product used for benchmarking is the robotic ankle H3 by Technaid shown in Figure 3. This product is also very similar to the previous product but doesn't have the same actuating system. Instead, the robotic ankle H3 uses a wave gear system to move the footplate. This product will also help our team design how the exoskeleton will attach to the user's legs. Using this products design can help us better model the dimensions of our exoskeleton design.

Figure 3: Robotic ankle exoskeleton H3

The third product used for benchmarking is the restore soft exosuit by ReWalk. We used this product for benchmarking since it was very different from the previous designs. Firstly, this product uses a Bowden cable actuating system to move the ankle. Then this product also uses calf wrap instead of a calf cuff like the previous two designs. Then instead of using a gear at the ankle this product uses two cables, which are meant to mimic the Achilles tendon and the tibialis posterior.

Figure 4: Restore Exosuit by ReWalk

The last product which we researched during our bench marking is the ultra-lightweight and versatile untethered robotic ankle exoskeleton. This product is similar to the Fully Active Chain and Sprocket Ankle Exoskeleton for Rehabilitation Assistance system, but instead of a complete chain system this design uses a chain to pulley system. Which is important since one of the customer requirements given is that our design needs to have a chain to pulley actuating systems. Which is one of the main reasons why we chose it for our benchmarking.

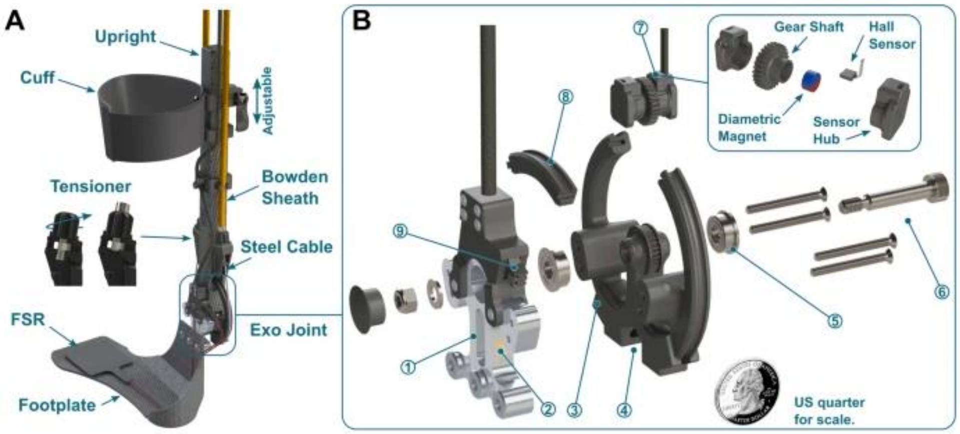


Figure 5: ultra-lightweight and versatile untethered robotic ankle exoskeleton

3.2 Literature Review

3.2.1 Diego Avila

Before designing the full exoskeleton, it was necessary to simplify the general design problem and calculate the torque acting on the human body. The following references provide equations and theorems that helped the team approach the problem and decide the best way to maximize biomechanical output and efficiency.

Mechanics of Materials[6]

The *Mechanics of Materials* textbook encompasses the introduction knowledge necessary to understand the reactionary forces from the contact of gears and gear train ratios. It was necessary to further understand torque and how it translates through gear trains.

Gear Ratio[7]

This pdf is a study guide developed by Professor Joel Kammet that covers the basic formulas for relating gear diameter and force to torque. It defines gear train ratios and the output speed and torque that results. This further develops the teams ability to decide the input necessary that would be able to have an output that can assist the walking motion.

Gear Train Ratio[8]

This article delves further into gear train ratio and provides real life application examples that utilize gears. A 1:1 gear ratio is not ideal for this project as it would require too much input torque to be a feasible application. In order to produce the necessary output power, it was beneficial for the team to analyze advanced applications of gear trains.

Fundamentals of Manufacturing[9]

The *Fundamentals of Manufacturing* textbook defines a process that the design team can reference when approaching the problem. An important aspect of designing biomechanical machines is identifying which manufacturing process best compliments biological structures. There are certain advantages of choosing the right development that work in favor of our project due to the fact that they affect the molecular structure of materials, reduce cost, or improve time efficiency

Previous Approaches[10]

Professor Dr Lerner has developed teams that consistently improve on previous approaches. Reported in detail on the NAU biomechatronics page is the complete process that the previous team took to improving the motor function of the ankle. By analyzing previous approaches through the engineering design process, it is possible to fix previous failures.

Gears in Nature[11]

It was very interesting to further understand how biological adaptations have developed gear systems within insects. In order to optimize power and synchronize its legs when jumping, some insects have gained an advantage in nature. Our objective is to mimic the efficiency of nature with our mechanical supplements.

3.2.2 Emma De Korte

For the manufacturing process and overall design, it is important to understand the various materials and material properties available. The resources used below were publications from previous teams that have created exoskeletons as well as textbooks and websites that contain material properties. Below are the multiple resources I used.

Mechanics of Materials [22]

The *Mechanics of Materials* textbook was used to understand different materials and how they perform in different scenarios. This book goes through how to calculate material deformation, strain and stress, and how thick materials might need to be in order to have minimal deformation. This was used to help determine how thick our material should be in order to perform under the needed farces.

Materials Science and Engineering: An Introduction [23]

The *Materials Science and Engineering: An Introduction* textbook goes into detail on various material properties and how they are made up. It also discuses the yield and ultimate strength of various properties and at what point the material might fail. This was specifically used to learn and understand the different materials the team was looking at, how each material performs under stress, and to help determine the needed thickness of materials.

Design Optimization [19]

This publication discussed one teams experience with designing an ankle exoskeleton and what worked and did not work for them. They also went into detail on what materials they were considering and what material they decided to use and why. This publication was specifically used to determine what materials might be helpful to look into and which ones should be used to perform calculations.

Design of a Passive Gait-based Ankle-foot Exoskeleton [20]

This publication goes through a professional ankle exoskeleton design with more advanced capabilities than our design. Their design contains a self-adaptive capability, and the publication goes into detail on how those functions within their design. However, this was specifically used to look at different motor assemblies that might be helpful to utilize within our design.

Untethered Robotic Ankle Exoskeleton [21]

This publication is of a robotic ankle exoskeleton that our sponsor and client helped create. Therefore, this publication was utilized to see what our client might be looking for with our design as well as how they went through the process to create it. This publication also had a motor schematic that was used to see what parts go into motor assemblies and what materials each portion was created out of.

Material Selections [24]-[35]

These websites contain all the information needed when determining the best material to continue with in our design. This included Vickers hardness score, the ultimate tensile strength, yield tensile strength, the cost of each material, and the density. These values were then used to be compared to each other to determine the material that fit all requirements needed.

3.2.3 Joscelyn Green

Before we can begin designing our ankle exoskeleton, we first need to understand how the body is used during walking. To get a better understanding of the anatomical system and what it takes to walk, I decided to do my literature review on the biomechanics of walking and the effects cerebral palsy has on the human body. Below are the 7 resources that I used to help us during our project.

Engineering mechanics: Dynamics [12]

This Engineering dynamics textbook was chosen, since understanding dynamics will be extremely useful during our calculations on the forces acting on the foot, ankle, and Achilles tendon during walking. This textbook goes over everything from how to calculate the forces acting on a moving object to the impact forces on an object. Which was very useful during my calculations of the torque acting on the Achilles during walking.

Biomechanics of Movement: The Science of Sports, Robotics, and Rehabilitation [13]

This textbook explains what biomechanics is and how sports affect it. Biomechanics is the science of the body and how ligaments, muscles, and tendons work together to create movement. Which is important since our ankle exoskeleton needs to be able to replicate these bodily functions. Which is why this book is so important for the design of our exoskeleton and our choice of actuating system.

Biomechanics of the ankle," Orthopedics and Trauma [14]

This journal explains in depth the biomechanics of the ankle and how it changes during running and walking. This journal also discusses the muscle involved with ankle stability Which is useful since it gives us information on the complete range of motion that the ankle follows during walking. Such information as the range of motion during walking is about 30° and increases as the movement becomes more strenuous.

Foot Biomechanics During Walking and Running. [15]

This is another journal that explains the biomechanics of the foot during walking and running. Which gives us information on the bending motion that occurs when you push off the balls of your feet during walking. Which is useful information during the calculation of the amount of force acting upon the Achilles tendon during walking. Which will help us during material selection of our pully system.

A REVIEW OF GAIT CYCLE AND ITS PARAMETERS, [16]

This journal helps to explain what a gait cycle is and what is involved during our gait cycle. A gait cycle is the cycle of walking from when the heel strikes the ground to shifting your body weight to the other side. This helps us understand how a person's body weight shifts during walking and how long it takes someone to go through an entire gait cycle while walking.

What is cerebral palsy?[17]

This website was created by the CDC to explain what cerebral palsy is and its effects on the human body. Which are symptoms like floppy or rigid limbs and involuntary bodily motions. Which is extremely important since our robotic ankle exoskeleton is designed for people ages 16 and below with cerebral palsy. Which allows us to design our exoskeleton with their symptoms in mind.

Biomechanical and perceived differences between Overground and treadmill walking in children with cerebral palsy [18]

This research article discusses the effects of cerebral palsy in children while walking. This document also shows how different cerebral palsy diagnoses can affect a person's gait length and ankle dorsal flexion. Which is useful during our design process to help us make our ankle exoskeleton more accommodating to more people with different diagnosis of cerebral palsy.

3.3 *Mathematical Modeling*

3.3.1 - Torque in Cables

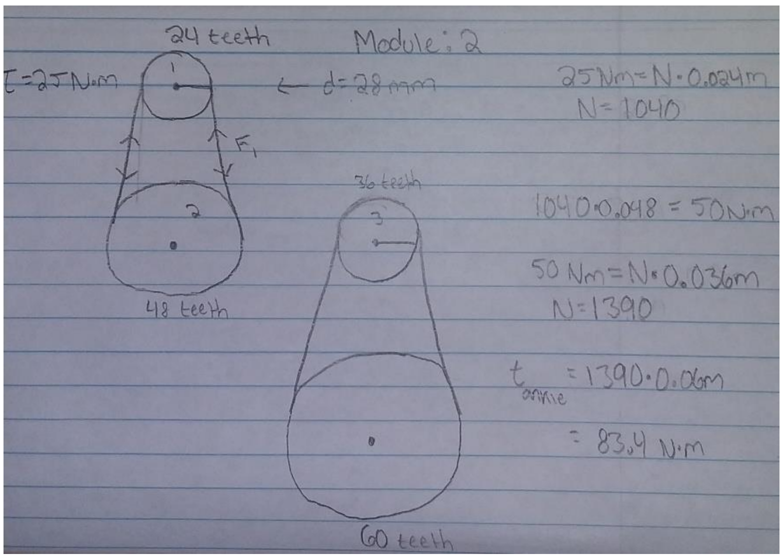


Figure 6: Gear train and tension in cables

A gear train is required for this project to be feasible. Two gears need a big size difference to produce enough torque to mimic the human ankle. As a result, gear trains are fundamental to approaching biological efficiencies and producing the necessary torque.

The gear train ratio is defined as (#of teeth in driven gear)/(# of teeth in driver gear) (1)

Torque is defined as T=F*D (2)

3.3.2 - Ideal cross section

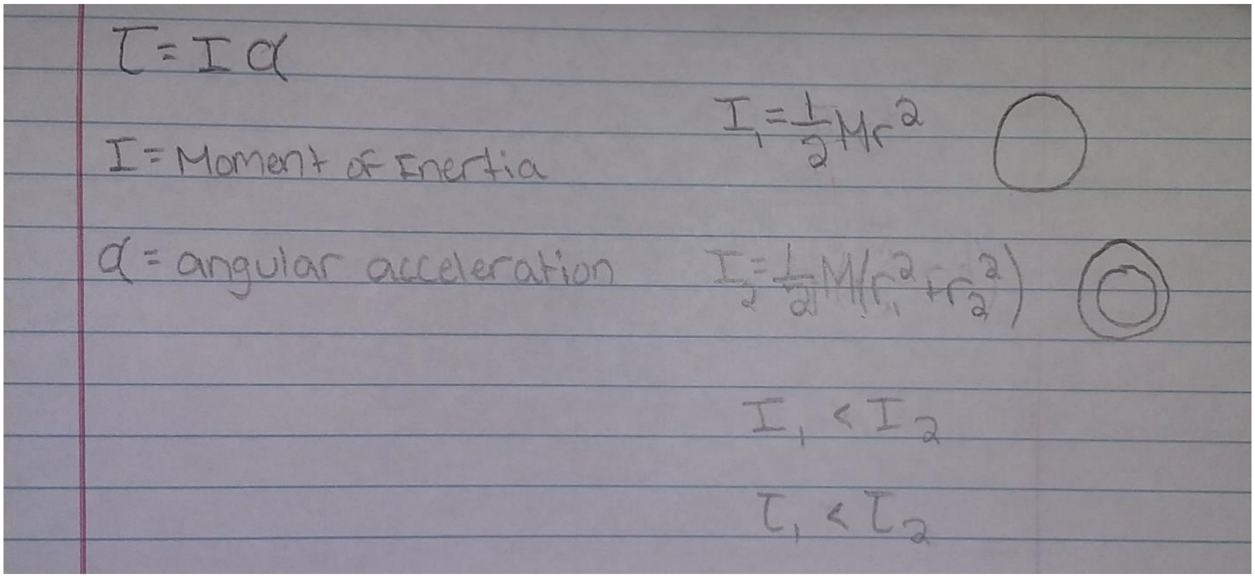


Figure 7

The analysis of cross sectional area was the first design development as that is where the last project sheared. The equations for moment of inertia of a solid circular cross section and a hollow cross section are respectively given as :

Solid: 0.5(mass)(radius)^2 (3)

Hollow: 0.5(mass)((outer radius)^2*(inner radius)^2)) (4)

3.3.3 Material Properties and Thickness of the Footplate – Emma De Korte

Each part of the motor assembly or ankle exoskeleton need to be made of a lightweight, strong material, and cost-effective material. In order to determine the best material to be used in the design, the team looked at four different materials, aluminum 6061-T6, low carbon steel, steel 4140, and titanium grade 5. All material properties used in determining the best material can be seen in Table 1.

Table 1: Material Properties [24]-[35]

Material	Hardness, Vickers	Ultimate Tensile	Yield Tensile	Density	Cost
Aluminum 6061-T6	107	310 MPa	276 MPa	2700 $\frac{kg}{m^3}$	$4.67-$252.94 (depends on thickness)
Low Carbon Steel	131	440 MPa	370 MPa	7850$\frac{kg}{m^3}$	$0.55 per kg
Steel 4140	207	655 MPa	415 MPa	7833$\frac{kg}{m^3}$	$0.55 per kg
Titanium Grade 5	349	950 MPa	880 MPa	4540$\frac{kg}{m^3}$	$50 per kg

From these properties, aluminum 6061-T6 was determined the best material to use as it is relatively lightweight, strong, and cost effective. Which match the customer requirements that need to be met.

Continuing with the design there is a footplate a part of the design. This will be provided by the client and is made of carbon fiber. However, the team wanted to determine the thickness that might be best for the success of the design. In order to determine the thickness, it is assumed an average 14-year-old male will best represent who will utilize the exoskeleton. This includes that mass, m, is 60kg, foot length is 24.45cm, foot width is 9.65cm, and the S=3.5 GPA or 3.5*10^9 Pa.

In calculating the thickness, the normal stress and acting force are needed to be calculated. Equation 5 calculated the normal stress, where F is the force exerted by the user and A is the surface area of the foot. Equation 6 calculates the force exerted by the user, where m is the mass, g is the gravitational acceleration, and μ is the friction coefficient of shoe against ground. The calculated force is 294N with the friction coefficient is 0.5.

$$\sigma = \frac{F}{A} \tag{5}$$

$$F = mgm \tag{6}$$

From the two above equations, the thickness can then be calculated using Equation 7. Where L is the length of the footplate or foot, S is the allowable stress of the material, and σ is the normal stress. From the calculated values, it was calculated that the needed thickness is 8.7*10^-4 mm. This value is very small, therefore the material used can be thin and will function under the conditions where the exoskeleton is used.

$$t = \sigma\frac{L}{S} \tag{7}$$

3.3.4 Force Acting on Bracket Designs – Emma De Korte

After coming up with four different designs of brackets that could be used. In order to determine the best design, it was important to perform a general force analysis to see which bracket might be best. In Figures 8-11, the four different designs analyzed can be seen.

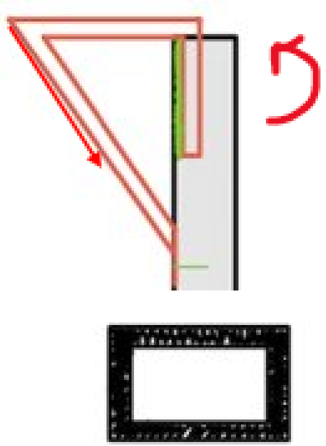


Figure 8: Design 1 Bracket and Cross-section

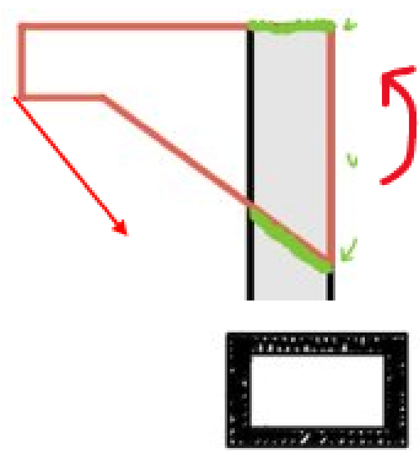
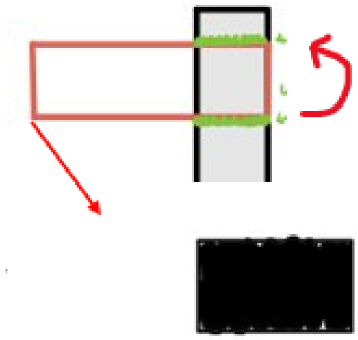


Figure 9: Design 2 Bracket and Cross-section



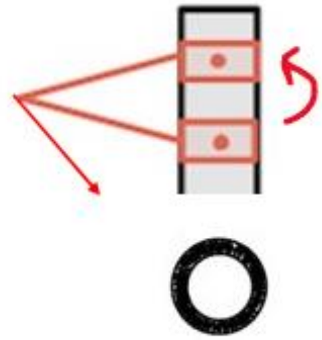


Figure 10: Design 3 Bracket and Cross-section Figure 11: Design 4 Bracket and Cross-section

The forces calculated were the acting forces in the x-direction and y-direction. (Equation 8 & 9). The directional forces were calculated utilizing F=388N, which was calculated within the mathematical modeling below and assuming that the 388N of force were acting in a 45º angle from the cable pulling downward on the bracket.

$$F_x = 388N cos(45^{\circ}) = 274.357N \tag{8}$$

$$F_y = 388N cos(45^{\circ}) = 274.357N \tag{9}$$

With the calculated directional forces and assumptions made, it is assumed that the bracket with the highest surface area attached to the carbon fiber tubing will disperse the force better, making it the best option within the design.

3.3.5 Torque acting on Achilles Tendon – Joscelyn Green

This mathematical modeling is to calculate the amount of torque acting on the Achilles tendon during the walking motion. The first step is to create a free body, which can be seen in Figure 12 below.

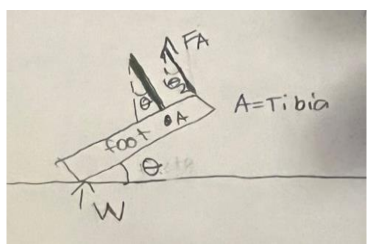


Figure 12: Free body Diagram of the Foot

Using this free body diagram, we can derive equation 1 to solve for the torque acting upon the Achilles tendon. The variable of equation 1 are W being the persons weight, which I used the average weight of a 14-year-old male. D1 being the distance from the balls of the feet to the tibia and D2 being the distance from the tibia to the Achilles. The variable θ being angle of elevation of the heel and θ_2 being the angle of the Achilles in relation to the tibia. The last variable is Fa which is the force of the Achilles. Using an ankle range of motion of 0-35° and putting these variables into MATLAB, we get graph (Figure 13) that tells us that the max torque acting upon the Achilles tendon is equal to 47.3 NM. Which will help us in choosing a motor and during the material selection phase.

$$-W \times D1\cos(\theta) + Fa \times D2\cos(\theta_2) = 0 \tag{10}$$

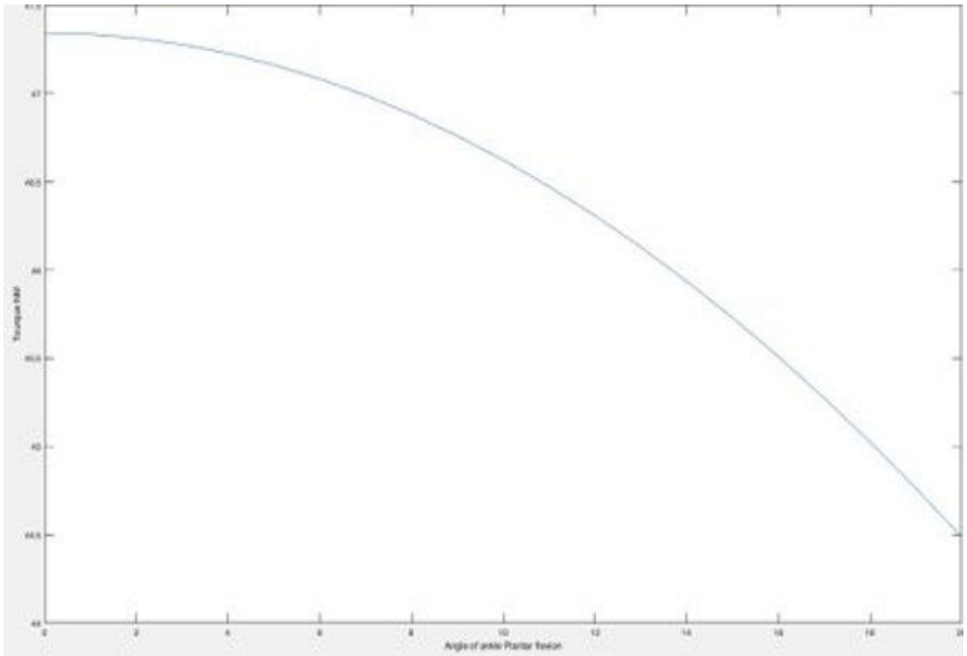


Figure 13: Graph of Angle of the ankle Vs Torque on Achilles Tendon

3.3.6 Shear Force at Attachment Point – Joscelyn Green

This mathematical modeling will investigate the best option of attachment method to use to attach our bracket to the rod. The first attachment method is using a bolt or rivet. Since these methods are very similar, we can use the same equation to calculate the shear force acting on them. To calculate the shear force acting on the bolt at the attachment point I used Equation 11. But before calculating the shear force, I first needed to find the force acting at that point. So, using Equation 12 with a torque value of 3.5, which was taken from the previous groups motor specifications and a gear radius of .009 m. I calculated a force of 388 N, but since the force isn't directly in the y direction, I had to use Equation 13 to find the force acting vertically at the connection point. Then using equation 2 with a factor of safety of 2 and bolt diameter of 9 mm, I calculated a shearing force of 8.61 N/mm^2 acting on the bolt. Which is well under the ultimate allowable stress of aluminum of 155 N/mm^2. Meaning that using a rivet or bolt is a viable option to attach our bracket.

$$\tau = \frac{F}{A} \tag{11}$$

$$F = \frac{Torque}{Radius} \tag{12}$$

$$Fy = F\sin(45°) \tag{13}$$

4 Design Concepts

4.1 Functional Decomposition

In order to better understand the design and functionality of an ankle exoskeleton the team created, and black box model and functional model were created. A black box model lays out the basic functional that needs to be performed by the device and then shows the material inputs/outputs, energy inputs/outputs, and the visual inputs/outputs.

The black box model for the robotic ankle exoskeleton is seen in Figure 14. The main function of the device is to assist in the walking cycle, also known as the gait cycle. The materialistic inputs are the foot, motor, and gears within the design, the outputs are the same. The energy inputs are biomedical or human energy, mechanical energy, and electrical energy. With the outputs beings biomedical (human) energy, mechanical energy, electrical energy, and thermal energy. The energy inputs and outputs are from the human utilizing the design, and the motor and chain/cable system functioning. Lastly, there are no visual inputs, however the outputs are whatever the sensor detects.

Figure 14: Black Box Model

After the black box creation, a functional model was created to expand on the functionality and inputs and outputs. The functional model can be seen in Figure 15. This model includes the functionality of the motor, chain/cable system, the functionality of the foot, and the sensors. The red boxed section is where our team specifically is focused on. This is the motor and chain/cable system. The main function in this section is hold the motor, let the motor run, while the motor runs the gears and chain/cable rotates, then the pulley activates. This cycle continues the entire time the exoskeleton is being utilized. Within this section, there is the motor and gear as the materialistic inputs and outputs. Thermal, electrical, and mechanical inputs and outputs are the energy inputs/outputs. These come from the motor outputting heat as it functions, the motor itself creating electrical energy, and then the mechanical system working. There are no visual inputs or outputs in this section.

The other sections focus on the foot moving with the exoskeleton and the sensors working with the design. As the foot moves and walks the exoskeleton is experiences biomedical energy as the human is inputting their foot. The other section has the sensor as the material input with electrical energy as the input/output and the visual output being whatever the sensors detect. While the team isn't focused on this portion of the design specifically, it is still a part of the overall robotic ankle exoskeleton.

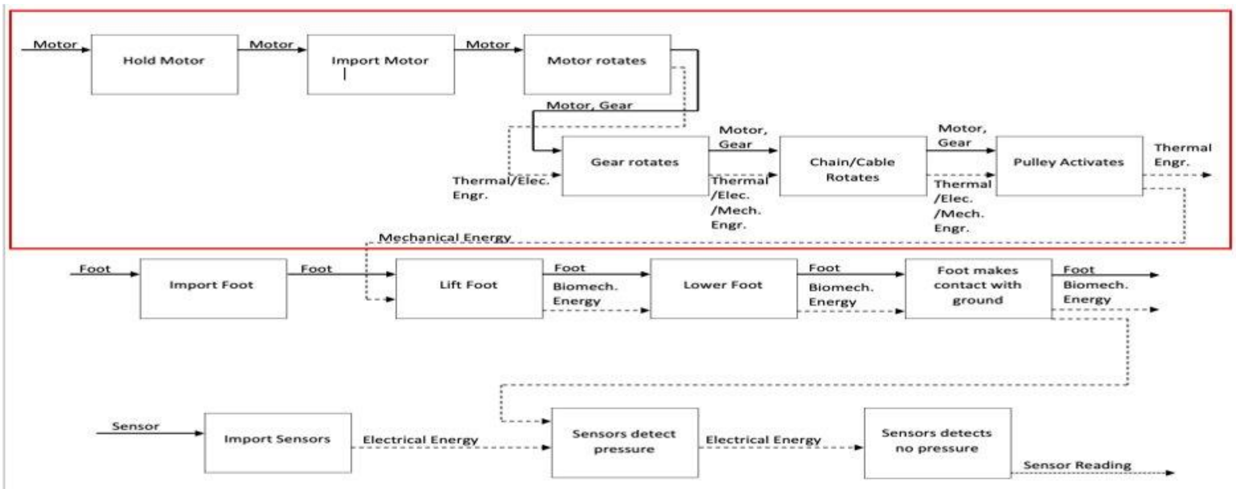


Figure 15: Functional Model

It is important to create the functional model and black box model as it helps the team better understand the overall design and how it should function. These designs tend to be created based on existing devices as the overall functionality is wanting to be replicated with improvements to the design.

4.2 Concept Generation

To begin our concept generation, we first need to split up our design into various subsystems. The subsystems that we came up with are the bracket design, the bracket cross section, and how the bracket will attach to the support bracket. Within these sub systems we came up with various ideas which we thought could be viable options. Listed below are the 3 subsystems, as well as our designs.

The first subsystem that will be looked at is the bracket design, which can be seen in Figure 16 below. Design one has a triangular shape that will attach through the top of the rod, as well as attaching to the outside. The second design has a similar shape but does not attach to the inside of the rod and also completely wraps around the rod. The third design will also wrap around the rod, but instead of a triangular shape it will have a rectangular shape. The fourth bracket design will have the same shape as the first design, but it does not attach to inside if the rod. Our last design will have two square collar brackets to attach to the rod, the bracket will also attach at one point and will branch out. These were the designs that our group came up with for how our actuating system will attach to the rod.

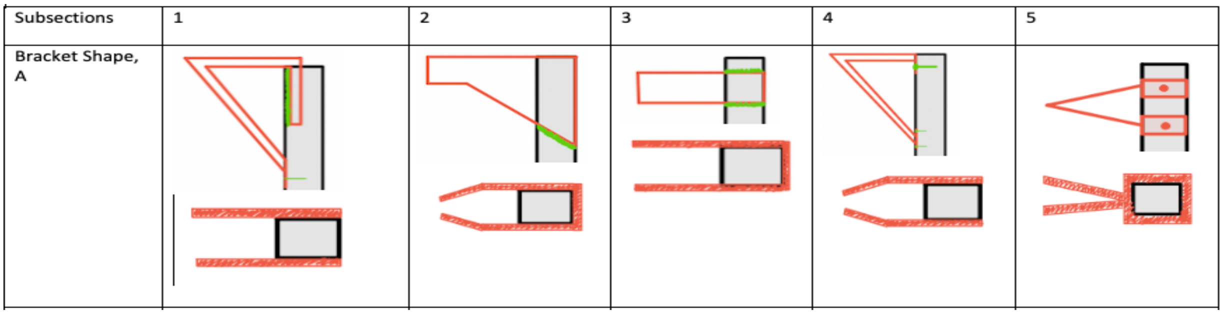


Figure 16: Bracket Design

The second subsection that will be discussed is our cross-section designs, which can be seen in Figure 17 below. The first cross section design is the bracket having a circular and hollow cross section. The second cross section design is a rectangular hollow design. The last design we have for our bracket is a rectangular cross section that is hollow.

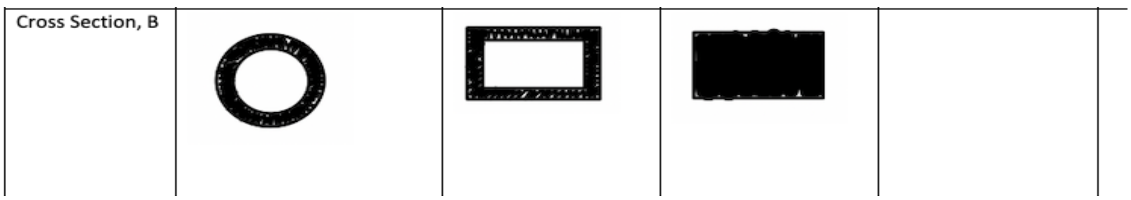


Figure 17: Cross section designs

The last design subsystem that we came up with is how the bracket will attach to the rod. These attachment type designs are shown in Figure 18 below. The first attachment type is using a rivet to attach the bracket to the carbon fiber rod. The second attachment type is using a bolt and hex nut to attach our bracket design. Then our last attachment type is using an epoxy to attach the bracket. Each attachment type has its own pros and cons, each will be explained during our selection criteria.

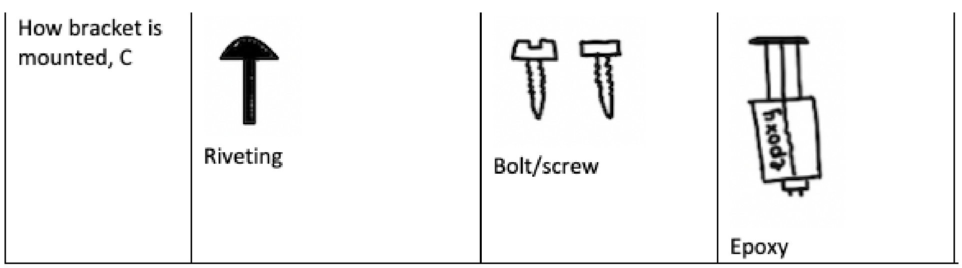


Figure 18: Attachment type designs

4.3 Selection Criteria

The selection criteria for our design were the overall engineering requirements listed and discussed above. For this conception generation cycle, the team focused specifically on the bracket design as that was the root of the testing flaws in the previous design. However, one customer requirement was no longer applicable to these designs. That was that the design needed to decrease the timing it take to remove the device, this was no longer needed as the client specifically wanted the bracket to be mounted to the carbon fiber tubing.

To determine whether or not the design was lightweight, the team determined how much material would be needed to create the overall design based on the images drawn. The more surface area the design had, the more material it was going to need, and the material costs will be more, therefore being heavier overall. However, if a design was more intricate, the manufacturing process would cost more, but the design itself would be more lightweight. To also determine the design would be lightweight, the density of the specific material chosen will aid in that.

The durability of the design relied on the overall shape of the design, the material of the bracket, and how the bracket is attached. Every material will be made from the same material, therefore that point is not important, but the team did look through four different materials and their properties to determine the best one. These are discussed in the material selection mathematical modeling. However, to determine the best shape, a force analysis was carried out on each design. It was found that is the same general force is acting at a 45º angle downward on the bracket, that each bracket would have the same x-directional and y-directional forces. As well as each bracket would have a positive moment on the attachment point. Therefore, the area will best determine the shape of the design.

Lastly, the bracket should be small in size in order to make sure the items do not exceed the 10cm threshold. This was evaluated based on the general surface area of each bracket. While specific calculations were not made in this area, the team used the visual of each design to determine the smallest area amount. This was able to be done, as each bracket was a different shape and not similar enough.

4.4 Concept Selection

To find the best design of the four created, a Pugh chart and decision matrix were created based on the selection criteria. The first round of concept selection was the Pugh chart, seen in Figure 19. A Pugh chart takes the design made by the team and compares them to a datum. Since the team is reiterating the previous design, the datum chosen was the bracket design from the previous team. Each design was then compared to the datum base on the selection criteria discussed above. The design was given a plus if it would the team felt it would perform better than the datum, a S if it would perform the same as the datum, and a negative if it would perform worse than the datum. These scores were given based on the mathematical calculations carried out and if the team felt it would do better, worse, or the same. After ranking each design, the total pluses, negatives, and same rankings were added up. Design 1 had three positives, and one same. Design 2 had two positives, one negative, and one same. Design 3 has four same. Design 4 has two positives and two same. The top two designs were then put into a decision matrix, these were Design 1 and Design 4.

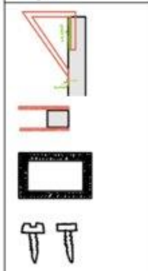
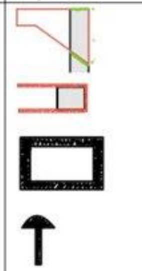
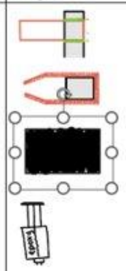
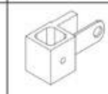
Pugh Chart	Design 1	Design 2	Design 3	Design 4	Datum
					
Lightweight	+	+	S	+	datum
Easy to take on and off	N/A	N/A	N/A	N/A	Datum
Durable	+	+	S	S	Datum
Cost Effective	+	-	S	+	Datum
Small in Size, close to body	S	S	S	S	Datum
$\Sigma+$	#	2	0	2	Datum
$\Sigma-$	1	2	0	0	datum
Σs	1	1	3	2	datum

Figure 19: Pugh Chart

The decision matrix (Figure 20) utilizes the same selection criteria as the Pugh chart. However, instead of ranking each design +, -, or S, they are given a ranking on a scale of one to ten. Each criterion is ranked on importance with the overall total being out of one or 100. The team gave light weight a score of 0.4, easy to take on and off, 0.05, durability, 0.3, cost effectiveness, 0.15, and small in size, 0.1. After each design was given a ranking one thru ten, the weighted score is calculated. Design 1 received an overall score of 8.55 and Design 4 received an overall score of 8.5.

		Design (1)		Design (4)	
Criteria	Weight	Score (1-10)	Weighted Scor	Score (1-10)	Weighted Score
Light Weight	0.4	9	3.6	8	3.2
Easily taken on and off	0.05	10	0.5	10	0.5
Durable	0.3	8	2.4	9	2.7
Cost effective	0.15	9	1.35	8	1.2
Small in size	0.1	7	0.7	9	0.9
Total	1		8.55		8.5

Figure 20: Decision Matrix

Since Design 1 had the highest score, the team modeled that bracket design within SolidWorks. That is seen in Figure 21. This design utilized a triangular shape where it attaches in the carbon fiber tubing up top and bolted into the tubing on the bottom. With a rectangular hollow cross-section.

Figure 21: CAD model of the final bracket design; Design 1

5 CONCLUSIONS

The team is reiterating a robotic ankle exoskeleton that was created during the 2021-2022 academic year, alongside the NAU Biomechatronics Lab. The team has gone through a literature review to help determine what areas of the design need to be focused and the beginning stages of mathematical modeling for specific areas of the design, as well as benchmarking to determine where our design can be improved against existing designs. A black box and functional model were created to understand the functionality of the exoskeleton. The team then went through a concept generation phase where there were multiple designs created based on three different sub sections. Then a Pugh chart and decision matrix were made in order to determine the best design to move forward with. Overall, currently the team will move forward with prototyping bracket design 1. Moving on, the team with 3D model the entire ankle exoskeleton within SolidWorks in order to determine if the design functions the way it is needed. After creation of the full design, an entire prototype will be created and tested prior to creating the final design.

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