Robotic Ankle Exoskeleton

Engineering Calculations Summary

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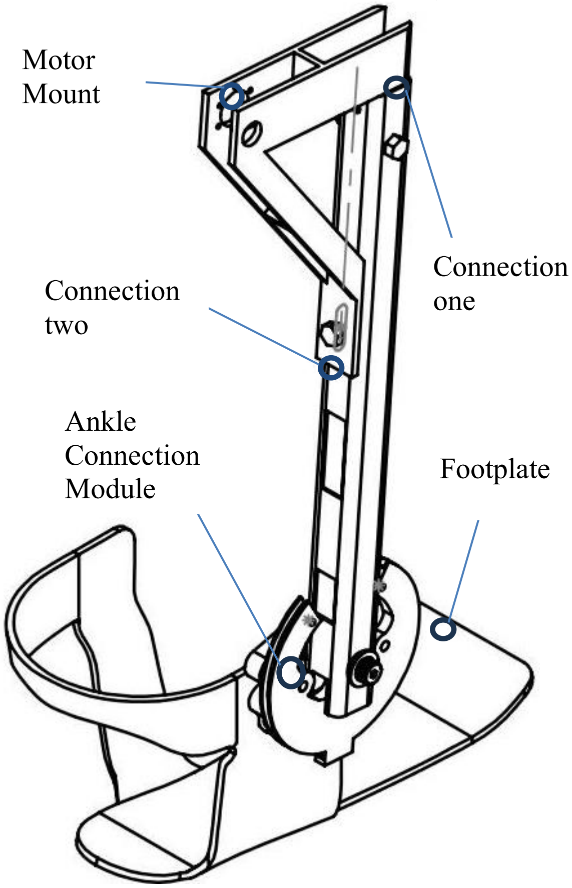
TABLE OF CONTENTS

Contents

1 Design Summary

There is the modern problem in which not everybody is able to travel and move about with the same ease and comfort as everyone else. Our clients with Cerebral Palsy have the physical inability to generate as much force in their lower extremities as the average person, but Professor Zachary Lerner has been coordinating with NAU's Biomechatronics lab to find a solution to that problem. Over several years, Dr. Lerner has developed and coordinated several iterations of an ankle exoskeleton that would supplement the biomechanical torque produced at the ankle while walking. This team developed a new approach to support the goal of building upon previous iterations in order to improve the walking gait of people who have cerebral palsy, by decreasing the amount of biomechanical torque that their body has to produce at the ankle through mechanical assistance. The previous bracket iteration broke under shear stress, and the Dr. Lerner wanted the motor to be in a specific position, so keeping those in mind, the 2024 exoskeleton capstone team produced a modified bracket that can be fitted with the existing components of the most successful existing model, shown in image 1. There are 5 main subsystems besides the new bracket and pulley: motor mount, connections one and two, footplate, and ankle connection module. The motor mount is going to be the only point of contact between the motor and the rest of the pulley and will have bores for the motor and gearbox to be attached to. Connection one and two are important introductions to the exoskeleton because they provide more base support against the bending and shear forces that the bracket braces against. Connection one uses the geometry of the carbon fiber tube as support by inserting the top of the bracket into the rod in order to reduce the effect of bending stress at that support, while Connection 2 braces against the carbon fiber rod to distribute force. The Footplate is to be taken from the previous iteration and is fitted with a pressure sensor allows researchers to quantify improvements in a person's walking gait. The Ankle Connection Module consists of the footplate, torque sensor, cable pulley, and carbon fiber rod. This is the section where the torque sensor is bolted to the footplate so that it can be the pivoting point for the rod and pulley. Once the pulley is bolted so that it is oriented the same direction as the footplate, the footplate will move when input torque is provided. Each subsystem is designed to meet given restrictions and requirements, with the ultimate purpose of providing additional torque to our client's gait from an electrical motor. The motor would receive input based on the clients walking cycle and activate a pulley system that would travel through the carbon fiber rod all the way to the ankle. This pulley would lift and push the footplate in sync with our client's steps. Besides improved efficiency, there were some general customer requirements for the product to meet in order to be marketable, as well as engineering constraints that had to be worked around.



Customer requirements

During our client meetings with Lerner, we discussed some of his requirements which he believes. our product should meet. These customer requirements are listed below.

-Lightweight

-Agronomical- Human Centered Design

-Durable

-Economical or Cost Effective

-Low profile- nonobtrusive to daily life

-Have a chain to pulley system

Engineering requirements

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)

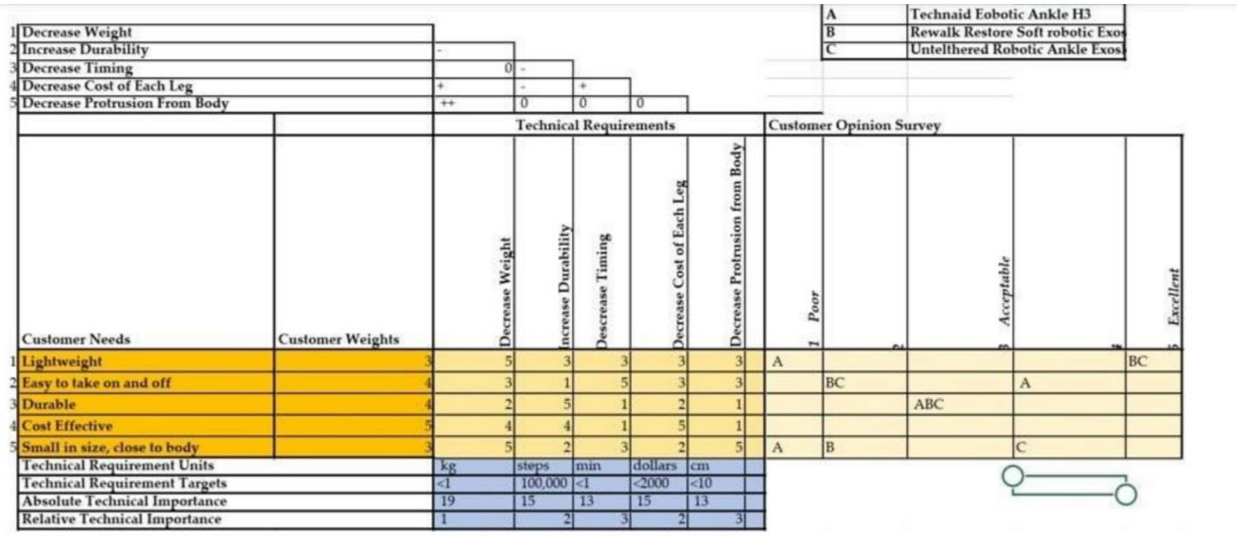
-Weight < 1 kg per leg

-Cannot extrude from the body more than 10 cm

-Lifetime of 100,000 steps

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

The above customer and engineering requirements were entering into a Quality Function Deployment table to determine which requirements had the most correlation between both parties. This was done to filter priorities and allow the team to decide on an approach to the solution. The QFD and its results are presented below.



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

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

			Technical Requirements						Customer Opinion Survey				
	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

2 Summary of Standards, Codes, and Regulations

2.1 Carbon Fiber Tube Standard - As9100 Rev D

As9100 Rev D, which comes from the aerospace standards is a document that certifies the quality of products made by this manufacturer. Specifically, the quality of manufactured composite materials. Which is important since knowing that the carbon fiber tube that we purchased will meet the aerospace standards for quality and will help our team have a safer final product.

2.2 Sprocket and Roller Chain Standards - ISO 606B & ISO 606

The standards for our drive chain and our sprocket come from ISO 606 and 606B. ISO stands for the International Organization for Standardization. ISO 606 provides the tolerances, dimensions, minimum strengths, as well as many other things for roller chains and their corresponding sprockets. Which gives us precise measurements for the chains and sprockets which we will be using on our device.

2.3 Hex Nuts and Washer Standard - Metric

The metric standard defines the appropriate size bolt to pair with this fastener to ensure a secure fit, by specifying the dimensions of the fastener, as well as listing a size grade and thread. This allows us to securely fasten our parts together while neglecting cracks at supports because the force is being distributed by washers.

2.4 Bearings Standard - AISI, ABMA, American Bearing Number

The standards for each bearing come from AISI and ABMA. These two standards assign bearing numbers to each bearing so that they can be easily codified by their inner and outer diameters, as well as properties such as max rpm and yield strength.

2.5 Steel Cable- AISI

The steel cable has to meet a certain standard in order to be a reliable design material. The steel cable can't have any excessive abnormalities, be the appropriate size, and have a specified strength. It is important to rely on the cable having a certain strength because the torque produced in this situation could shear certain materials of lesser strength.

2.6 Motor and Gear Box – IEC

No specific standards were found for the specific motor and gearbox being used within this project; however, it was found that most motors need to follow an International Electrotechnical Commission (IEC) standard. These standards are utilized to ensure the motors are efficient and safe to use.

2.7 Bracket – ISO 2768

To help with manufacturing the bracket, ISO 2768 is a standard that will be utilized. This standard is an international machining standard that helps provide standard machining tolerances. Therefore, help provide insight on the tolerances the team might use in order to follow general machining practices. [3]

2.8 Exoskeleton and Human Testing – ASTM International F48

ASTM International F48 is a combination of standards that define an explain the implications and how exoskeletons can be used. The standard references ISO 13482 as a different criterion that can be used, however it does not fully encompass how exoskeletons are used and tested. This standard is used in order to guide the team in creating a device that is safe for the users. [4]

3 Summary of Equations and Solutions

3.1 Bracket Analysis

The conditions that were applied to our bracket during our FEA analysis, where if our motor and gearbox were producing the max intermittent torque of 3.5 NM. Using this torque value and the dimensions of the sprocket driven and Equation 1, I calculated the force generated by the motor. After finding the forces generated by the motor, I used our bracket model with the correct material within SolidWorks and using the FEA tool was able to analyze our bracket under the forces applied which can be seen in Appendix A. But to do this I made assumptions such as the forces being equal at every point where the forces would be active, instead of the forces varying. By doing this it allowed us to find the factor of safety of our Bracket.

$$F = Torque \times Radius\,(\,) \tag{1}$$

3.2 Attachment screw analysis

This is an analysis on the factor of safety of our selected attachment screws which will attach our motor to our carbon fiber rod. The condition of this calculation is that all the forces acting on the bracket will be applied to a single point and the motor is also producing maximum torque output. The first step is calculating the forces, which was done using Equation 1 listed above. After calculating the force generated by the motor, I then needed to calculate the forces acting in the y-direction using Equation 2 below. Then using the force in the y-direction and the area of our select screw, I was then able to calculate the shear stress on the screw using Equation 3 listed below. Then using the calculated shear force and the material properties I was then able to find the factor of safety for our screws.

$$Fy = F \times \ cos\theta \tag{2}$$

$$\tau = \frac{F}{A} \tag{3}$$

3.3 Sprocket Analysis

This analysis will look at the forces acting on the teeth of our sprocket which is pulling our roller chain. This analysis was done under the condition that the motor and gearbox were outputting the maximum intermittent torque. Using this condition, the dimension found for our sprocket, the forces found above, and the Lewis form factor I was able to calculate the force acting on the teeth of the gear using Equation 4-5. Then using this bending stress and the material properties of the sprocket I was then able to find the factor of safety for our sprocket.

$$\sigma = \frac{W^t P}{FY} \tag{4}$$

$$P = \frac{Number\ of\ Teeth}{Pd} \tag{5}$$

3.4 Torque in Cables

During the beginning of the project, one of the first steps taken was determining how much torque would have to be produced in order to propel the average person in their walking gait. This was calculated by estimating the weight that would be used, as well as taking the average length of a foot to find the necessary output. While communication was fresh between the team and our client, the necessary torque was calculated, a method to produce it was drawn up, and the factor of safety came out to be 83.4/80.6 = 1.03.

$$Gear\ Ratio = \frac{\#\ of\ Teeth\ in\ driven\ gear}{\#\ of\ Teeth\ in\ driver\ gear} \quad (6)$$

$$T = F * D \quad (7)$$

3.5 Ideal Cross Section

The structural integrity of the motor mount bracket was of special interest to this team as the bracket was the failing component in the last iteration of the exoskeleton. Looking at geometric strengths, the team decided to design hollow square bracket because it would have the strongest geometry and be the easiest shape to attach to the footplate and calf cuff. The yield strength of the rod was calculated using the area moment of inertia of a circle and ring to determine if hollow or solid rods are stronger, and then deciding that a square is most practical to use as an exoskeleton.

$$I = \frac{1}{2}M * r^2 \quad (8)$$

$$I = \frac{1}{2}M(r_1^2 + r_2^2) \quad (9)$$

3.6 Bracket Material Selection

To determine the best material the bracket should be made out of, the team looked at the properties of four different materials. In order to match the customer's requirements, the material needed to be lightweight, strong, and cost-effective. The four materials examined are, aluminum 6061-T6, low carbon steel, steel 4140, and. Titanium grade 5. In Table 1, the materials properties can be found, from this, and research of materials commonly used in exoskeletons, aluminum 6061-T6 was selected. A FoS analysis was done on the bracket, as seen above, utilizing this material. Therefore, solidifying the selection.

Table 1: Material Properties of Four Different Materials

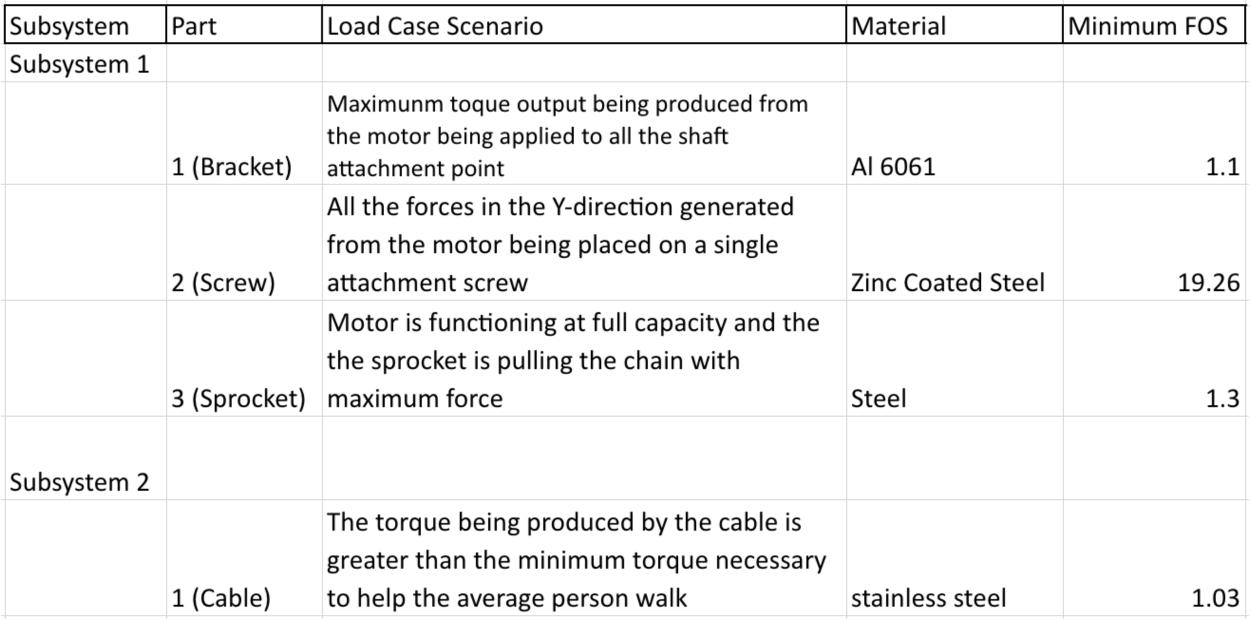
Material	Hardness, Vickers	Ultimate Tensile	Yield Tensile	Density	Cost
Aluminum 6061-T6	107	310 MPa	276 MPa	2700 $kgm3$	\$4.67-\$252.94 (depends on thickness)
Low Carbon Steel	131	440 MPa	370 MPa	7850 $kgm3$	\$0.55 per kg
Steel 4140	207	655 MPa	415 MPa	7833 $kgm3$	\$0.55 per kg

Titanium Grade 5	349	950 MPa	880 MPa	4540 $kgm3$	$50 per kg

3.7 Factor of Safety

In Table 2, all the factor of safety's discussed above can be found.

Table 2: Factor of Safety



Subsystem	Part	Load Case Scenario	Material	Minimum FOS
Subsystem 1				
	1 (Bracket)	Maximunm toque output being produced from the motor being applied to all the shaft attachment point	Al 6061	1.1
	2 (Screw)	All the forces in the Y-direction generated from the motor being placed on a single attachment screw	Zinc Coated Steel	19.26
	3 (Sprocket)	Motor is functioning at full capacity and the the sprocket is pulling the chain with maximum force	Steel	1.3
Subsystem 2				
	1 (Cable)	The torque being produced by the cable is greater than the minimum torque necessary to help the average person walk	stainless steel	1.03

4 Flow Charts and other Diagrams

To determine the functionality of the exoskeleton, a functional decomposition model was created. This diagram helps to map out the different sections of the design and how they function separately and together. The different sections include the motor functionality, foot functionality, chain and cable system, and the sensor system. Our team is specifically focusing on the red boxed section. The other portions are still needed in order for the exoskeleton to function, however those area is provided to us. The boxed section includes the motor, bracket, and chain/cable systems. With the motor and gear/sprocket being the material inputs/outputs, thermal, electrical, and mechanical energy as the energy input/outputs, with no visual input/outputs.

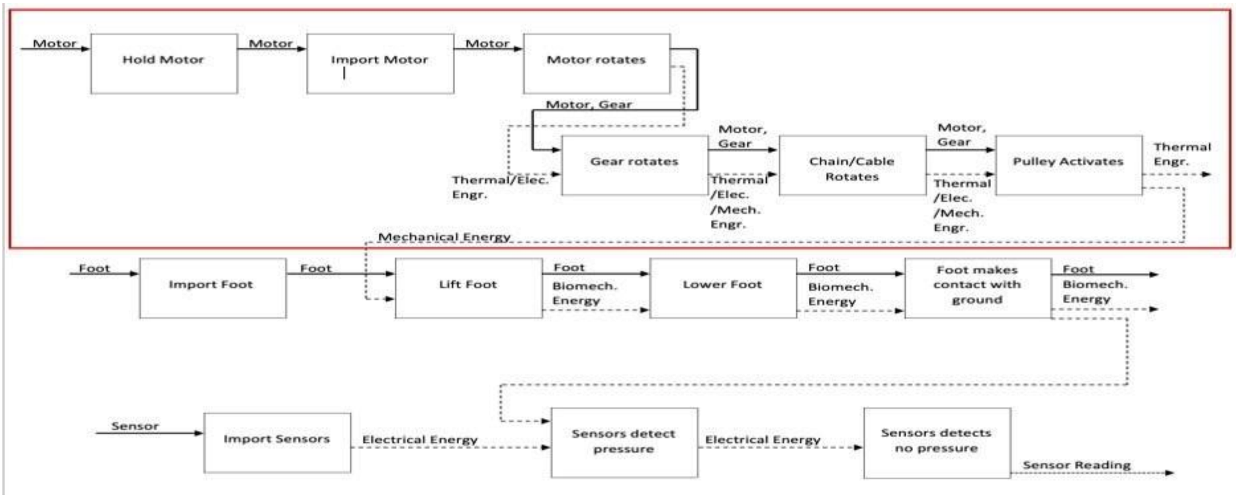


Figure 1: Functional Decomposition

5 Moving Forward

Moving forward, our team plans on doing more analysis on our design. The first analysis that we plan on doing is a FEA analysis on the pulley which will be used for our device, using the tension force from the cable to find if our pulley stopper will fail under extreme conditions. The second analysis that we plan on doing is redoing our FEA analysis on our bracket. We plan on redoing this analysis since we increased the thickness of our bracket as well as we plan on removing material from our design to make it lighter. So, we need to make sure that our design will still have a factor of safety greater than 1 after our alterations. We also plan on redoing our FEA analysis on our carbon fiber rod, since we also made some alterations to the dimensions of some of our cuts in the rod. Redoing some calculations as well as doing new ones will allow our team to create a device that will function in the worst-case scenarios.

6 Citations

[1] Rockwestcomposites Standards, https://www.rockwestcomposites.com/downloads/A-42_12K_(07-11-2012)_RWC-PN-13000.pdf (accessed Jan. 25, 2024).

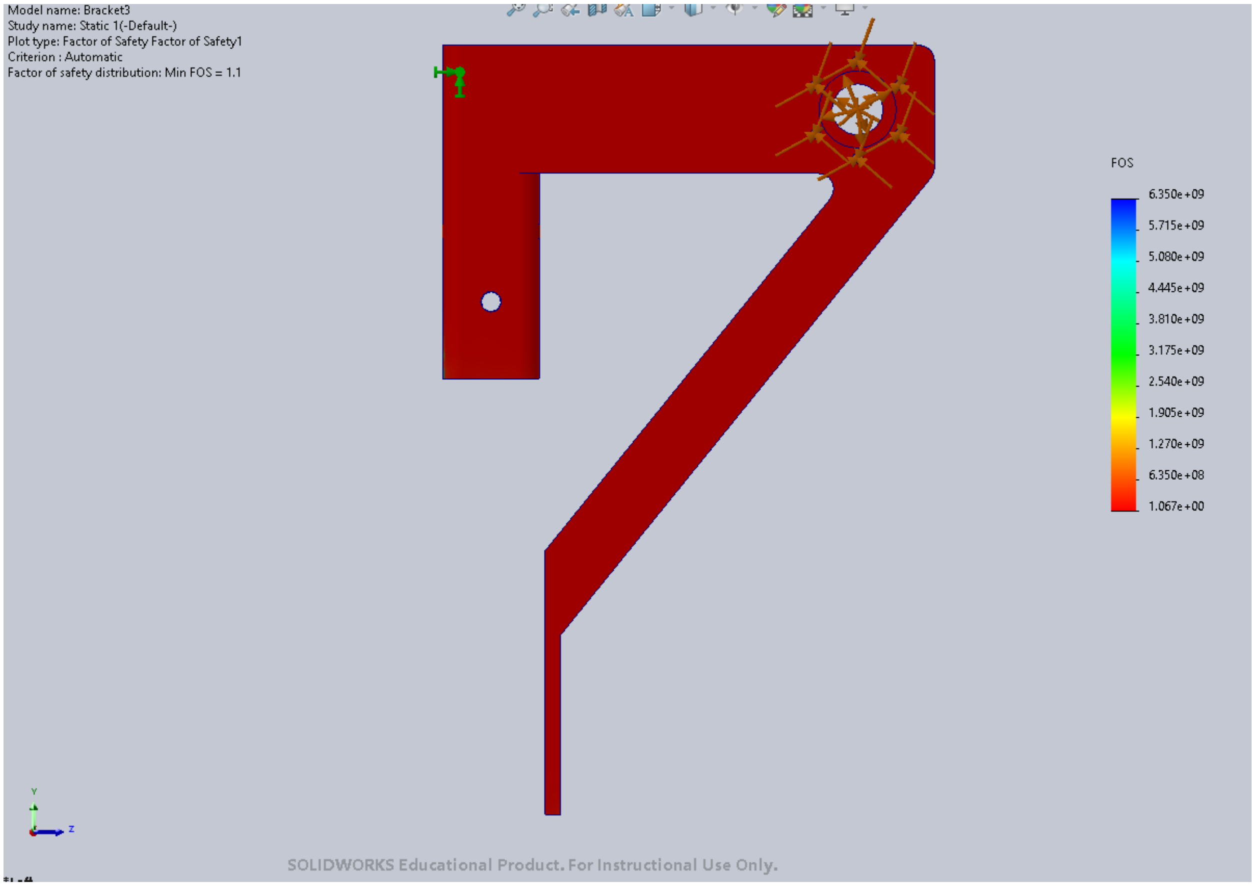
[2] “International Organization for Standardization,” ISO, https://www.iso.org/home.html (accessed Jan. 24, 2024).

[3] T. Axsom, “What is ISO 2768?: CNC Machining Tolerance Standards,” Fictiv, https://www.fictiv.com/articles/iso-2768-an-international-standard#:~:text=ISO%202768%3A%20An%20International%20Standard&text=It%20is%20an%20international%20manufacturing,for%20manufacturing%20costs%20as%20well (accessed Jan. 26, 2024).

[4] “Exoskeletons and EXOSUITS research and Standard Test Methods,” NIST, https://www.nist.gov/el/intelligent-systems-division-73500/exoskeletons-and-exosuits-research-and-standard-test-methods (accessed Jan. 26, 2024).

7 Appendix

Appendix A



Model name: Bracket3
Study name: Static 1(-Default-)
Plot type: Factor of Safety Factor of Safety1
Criterion : Automatic
Factor of safety distribution: Min FOS = 1.1

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