Faculty of Engineering and Applied Science

Design Project: Group Report

ENGR 3030U

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1. Background and Motivation

The objective of this project is to design an upper-body exoskeleton tailored for individuals who experience mobility limitations due to conditions such as muscular dystrophy, arthritis, or post-stroke motor impairment. These conditions often reduce muscle strength, coordination, or endurance, making it difficult to perform everyday tasks like lifting objects, carrying groceries, or completing basic household activities. Our exoskeleton addresses these challenges by redistributing the load from the arms and hands to the upper torso, reducing ergonomic strain while improving functionality.

Figure 1: Levitate Airframe Exoskeleton

Inspiration and Vision

The concept for this project was inspired by observing the limitations of current systems in addressing the needs of individuals with mobility impairments. While devices like the Levitate Airframe excel in industrial environments, they fail to cater to users requiring assistance for everyday tasks. By rethinking the application of exoskeleton technology, we aim to create a device that empowers users to regain independence and perform tasks with reduced strain on their hands and arms.

This project represents a step toward democratising exoskeleton technology, making it affordable and accessible for personal use. It has the potential to transform the lives of individuals with conditions such as rotator cuff injuries, Parkinson's disease, or cerebral palsy, enabling them to carry out daily activities with ease, safety, and dignity. By leveraging mechanical simplicity, ergonomic design, and cost-effective materials, our exoskeleton offers a unique and practical solution to a long-standing problem.

Current State of the Market

Existing exoskeleton designs, such as the Levitate Airframe, have successfully demonstrated their ability to reduce stress and fatigue for industrial workers, particularly in manufacturing and construction environments. These devices provide ergonomic support, enhance productivity, and reduce the risk of musculoskeletal injuries during tasks requiring overhead motion or repetitive lifting. Companies like BMW, Toyota, and John Deere have already adopted these systems for their employees, underscoring the effectiveness of this technology.

However, the Levitate Airframe and similar industrial-grade exoskeletons are designed primarily for professional use, often incorporating advanced features like multi-degree-of-freedom motion, high torque, and integrated motor systems. These features come at a cost—both financial and practical. Their high price point, bulkiness, and reliance on motors and electrical systems make them inaccessible for personal use, particularly for individuals requiring assistance with daily tasks.

Addressing the Gap

Our project aims to bridge the gap between high-end industrial exoskeletons and the unmet needs of everyday users. Unlike existing systems, our exoskeleton prioritises simplicity, affordability, and user-friendliness. By eliminating unnecessary complexity and focusing on basic mechanical components, we ensure that our design is accessible to a broader range of users, including individuals with mobility limitations or financial constraints.

Key improvements over existing designs include:

- Weight Distribution: Inspired by the functionality of a traditional shoulder yoke, our design distributes weight evenly across the trapezius and upper torso rather than isolating support to specific areas like the arms or shoulders. This approach not only improves load-bearing capacity but also enhances user comfort during prolonged use.
- Simplicity and Cost: By using readily available materials like 6061-T6 aluminium and 3D-printed PLA, our exoskeleton maintains a lightweight yet durable structure. This ensures it is both robust and cost-effective, capable of supporting loads of up to 150 lbs per arm without reliance on motors or electrical components.
- Focus on Accessibility: Our design shifts the focus from industrial applications to personal assistance, making it suitable for rehabilitation, household tasks, and general load-carrying activities.

Figure 2: Human Yoke for Load Distribution

Evaluation of Design Targets

During the development phase, the team compared existing device specifications and identified potential areas needing improvement. These insights were then carefully applied to our own design, aiming to emphasize ease of use, functionality, as well as affordability. For example, the exoskeleton's hook and strap system was refined to improve load transfer while ensuring user comfort. These enhancements resulted in the creation of a device that was ergonomic, user-friendly and that met the functional requirements of our target base. By addressing the shortcomings of current systems and prioritizing user needs, this exoskeleton is uniquely positioned to enhance daily activities for individuals with neuromuscular challenges.

1. Design

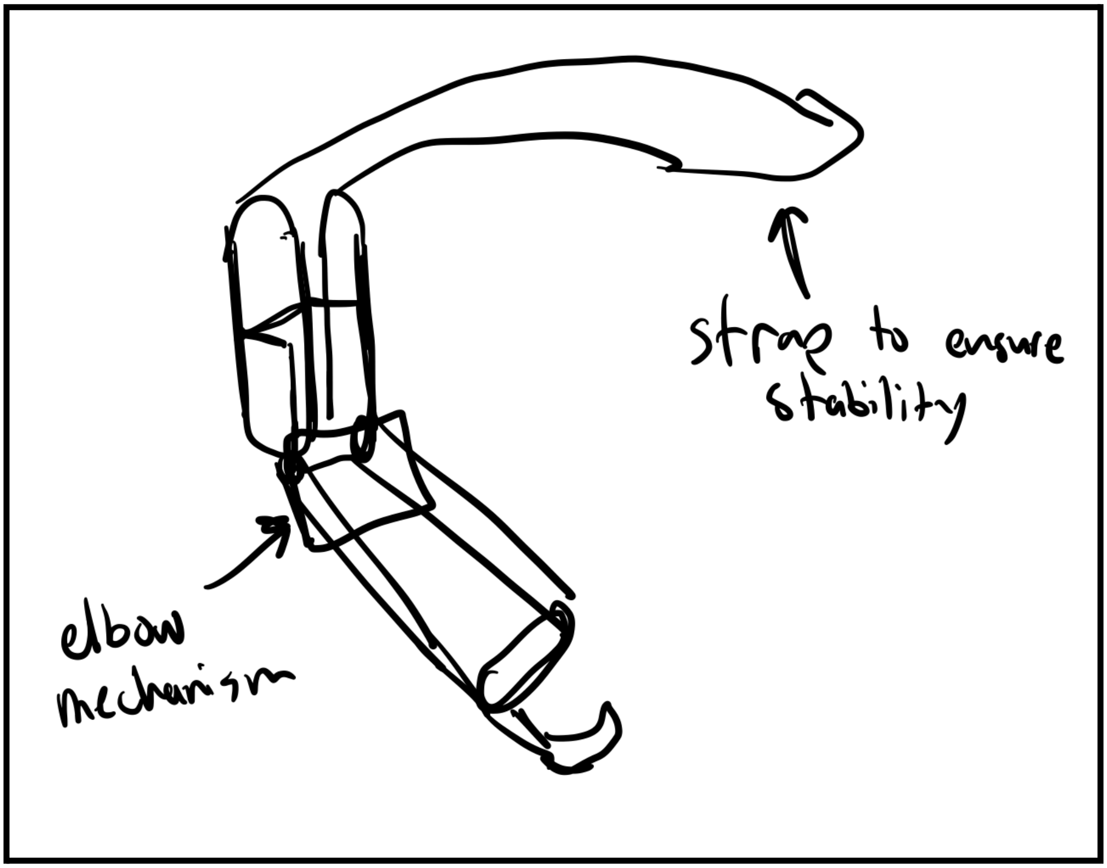


Figure 3: Initial Design Sketch

The initial goal for our design was to create an exoskeleton arm which combined the features of previous, more common exoskeleton arms, together. Exoskeleton arms typically only had bicep flexion support, shoulder adduction shoulder, or load carrying capacity assistance. In our initial design, we knew we wanted to combine at least two of the features and the two features we combined were load capacity assistance and bicep flexion support. Later on in the design process, shoulder adduction abilities were added to the Exomen arm.

Forearm Frame

Rings:

The first geometry of which all other parts were based on was the arm rings around the wrist. The average measurement of wrist diameter in our group was taken as ~7 cm and 3cm more was added to ensure comfort. The rings gradually increase as we go up the arm because the further along the forearm you go, the larger the diameter of the forearm becomes. The same procedure for obtaining an appropriate diameter was done and a diameter of 120mm was used. Later on in the design process, the last ring closest to the elbow was removed due to safety concerns which are discussed in the safety and risk section.

Plank:

Planks were designed and attached to the forearm rings to ensure stability and strength. Parametric curves were used on the planks to increase aesthetic appeal. The distance from the elbow to the palm subtracted from the distance from the hand grasper to the connection point between the grasper and the forearm frame was used for the length of the plank. A length of 260mm was measured. This measurement was taken from the member in our group who would be performing the demonstration of the Exomen arm. The planks were also made with aluminium to ensure strength and rigidity of the frame as they would be subjected to more stress than other parts of the design.

Bicep Frame

The bicep frame runs along the bicep of the user's arm and the length of the arm was measured from the elbow of the demonstrator to the demonstrator's shoulder. Supporting rings were added to the bicep frame to ensure rigidity and strength of the bicep frame.

Bicep Flexion Mechanism

The bicep flexion mechanism was one of the concepts in our design that required the most consideration. Some of our ideas included the use of springs, a pneumatic cylinder, water syringes, and linear actuators.

Springs:

Springs were not chosen as they would have allowed us to perform bicep flexion in one direction but not the other. We wanted the whole bicep flexion movement to be assisted, not just one motion, because when lifting heavy loads, having assistance in one direction only isn't enough to guarantee safety for the user.

Pneumatic Cylinder:

Pneumatic cylinders were considered for their strength and speed of flexion but ultimately were not chosen. The reason that they were not chosen is because it was too bulky. The pneumatic cylinders needed for our design would have needed to have a tank of compressed air nearby, which is far too cumbersome for our design.

Water Syringes:

Water syringes were considered as they were suggested to us by our project consultant due to their portability, cheapness, and simplicity. However, we opted not to use water syringes as they were too weak for our applications and the stroke length we needed would require custom fabrication of a syringe plunge to have a stroke length of 50mm. The stresses which would be acting on a 50mm plastic syringe plunge were deemed to be too much for the material to handle, as the long stroke length would increase the torque on the plunge. Additionally, it proved to be very complex to create the bicep flexion movement using water syringes, as you would need to create a mechanism to pull the plunge on the bicep frame instead of pushing it. This means that the plastic material would be under even more stress, as they are flimsy when pulling under a high load.

Linear Actuator:

Linear actuators were chosen for their simplicity, cost effectiveness, and strength. The linear actuator we selected had a stroke length of 50mm but also had different stroke lengths to choose from which increased the flexibility of using a linear actuator. The linear actuators also had a stroke material made from aluminium and a load capacity of 225 lbs which makes them strong enough to handle all of the tasks that the Exomen arm will be completing, especially for the demonstration where we will be lifting a dumbbell. One downside of the linear actuators is that some wiring is needed to connect it to a battery and on/off switch. Another downside is that the actuator moves the stroke at 10 mm/s which is very slow compared to the other methods. However, we determined that the linear actuator would be excellent for the first prototype to ensure strength and usability of other components along with a usable bicep flexion mechanism.

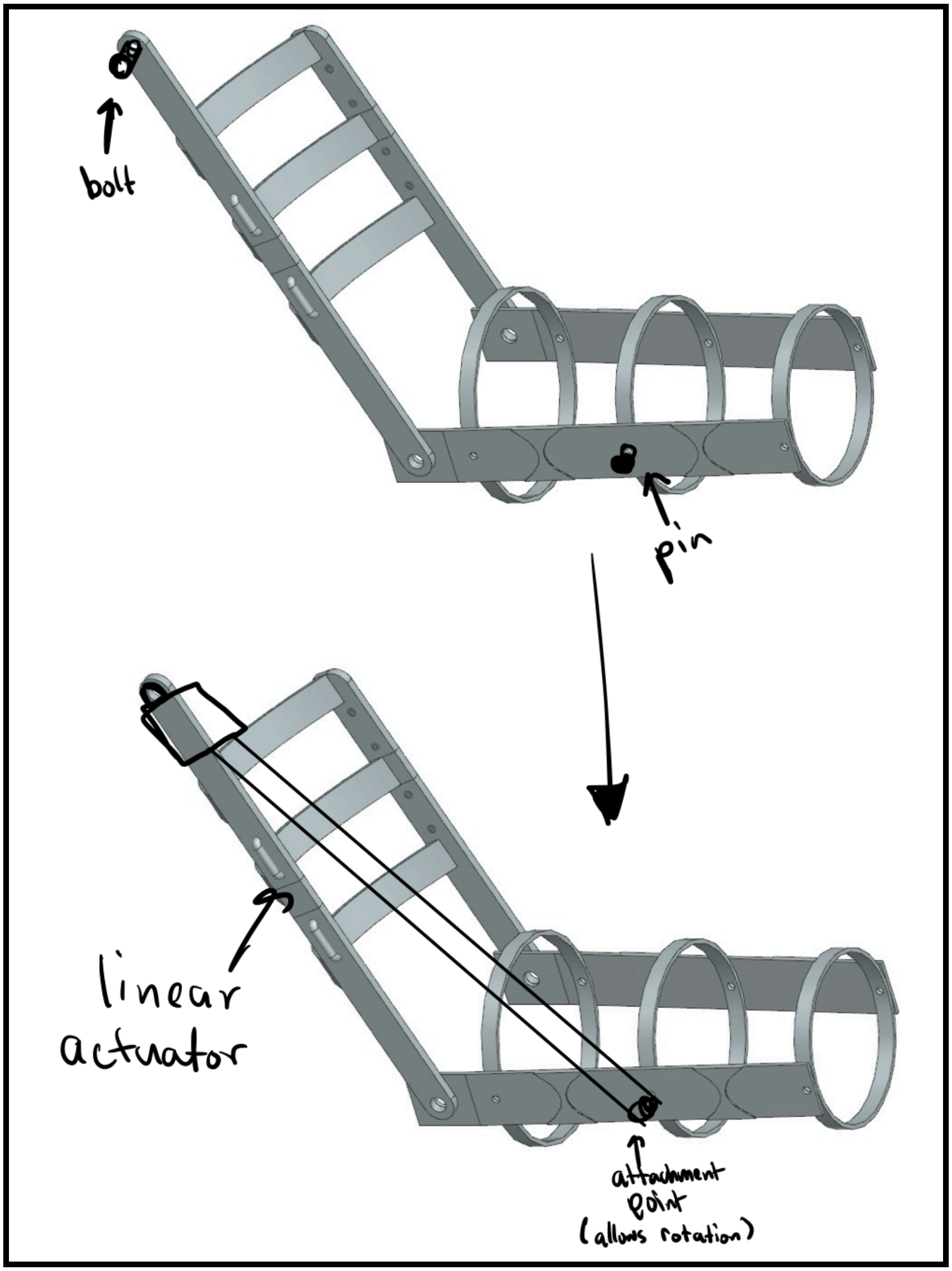


Figure 4: Bicep Flexion Mechanism

The bicep flexion mechanism was achieved from the use of a linear actuator. The linear actuator was fixed at an angle to the side of the bicep frame and connected to a cylinder attachment point which was perpendicular to the plank. The cylindrical attachment point had fixed translation but allowed rotation in the axis about the attachment point's axis.

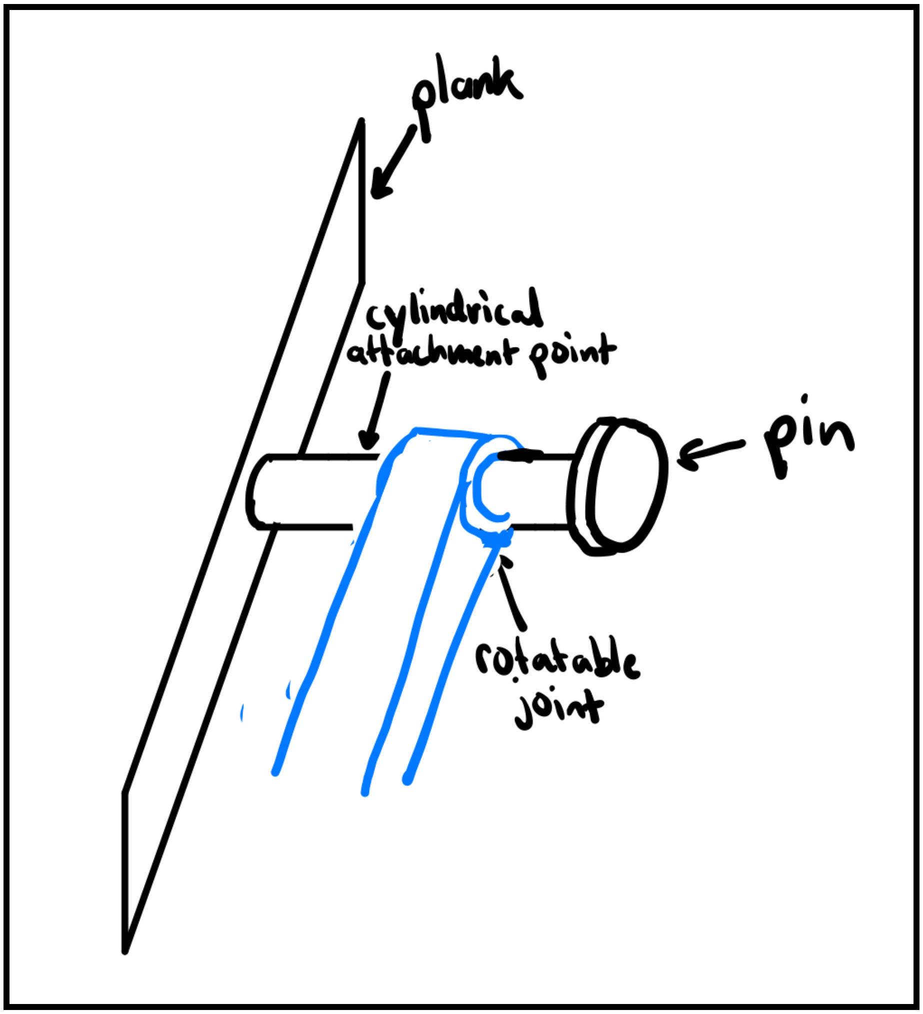


Figure 5: Attachment Point for Linear Actuator

As shown in Figure 5, the linear actuator is attached to a rotational joint which is connected to a cylindrical attachment point normal to the plank. The rotatable joint allows the forearm frame to hinge at the elbow, as if it wasn't rotatable, it would pull the entire forearm frame without rotating it. The distance between the rotatable joint and the plank and rotatable joint to the stopper are exaggerated in the diagram as the mechanism wouldn't be clear if it was drawn to scale. The rotatable joint would not have any room to move side to side in the actual design.

The demonstration weight for the Exomen was chosen to be a 4.5 kg dumbbell. To calculate the force needed from the linear actuator to lift this load, we calculated the torque applied from the 4.5 kg dumbbell onto the forearm frame. The force of the dumbbell, F_dumbell was calculated as follows:

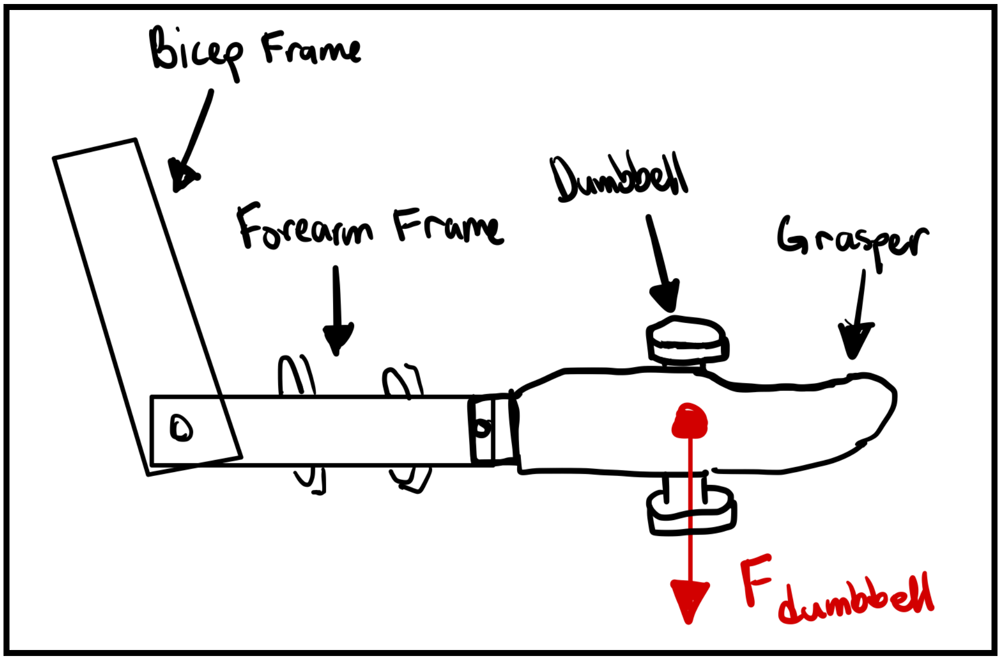


Figure 6: FBD of Dumbbell in Exomen Arm

$$F_{dumbbell} = m_{dumbbell}a$$

$$F_{dumbbell} = (4.5\ kg)(9.81\ m/s^2)$$
$$F_{dumbbell} = 44.145\ N$$

The torque due to the dumbbell at the pivot point located at the elbow was then calculated in order to find the torque needed to lift the load. The torque at the pivot point, T_dumbbell, was calculated as follows with r being equal to ~320mm (elbow joint to dumbbell holding jaw):

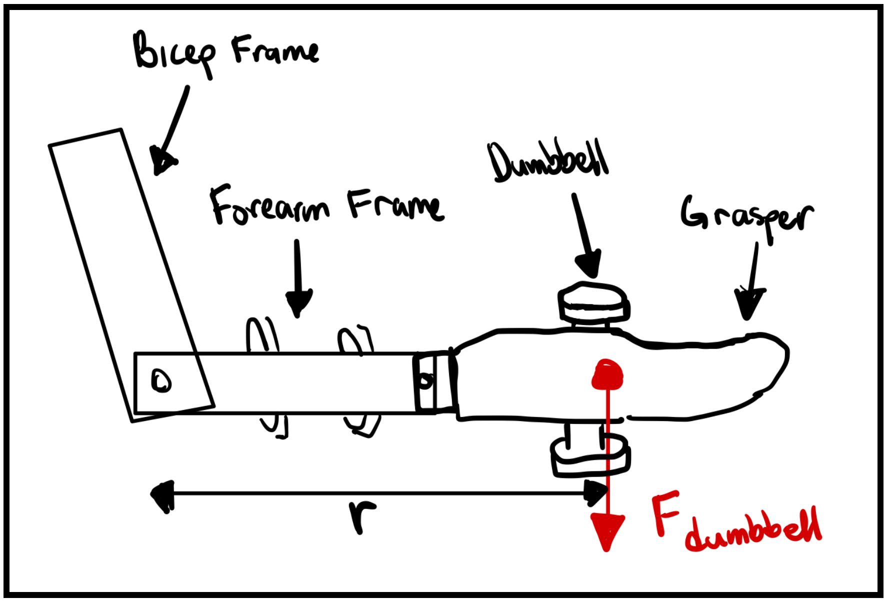


Figure 7: Calculation of Torque Generated by Dumbbell

$$\tau_{dumbbell} = rFsin\theta$$

$$\tau_{dumbbell} = (320x10^{-3}m)(44.145\,N)$$

$$\tau_{dumbbell} = 14.13\,N \cdot m$$

The force of the linear actuator, F_actuator, was then calculated by using the torque generated from the dumbbell in order to find the minimum force required to counterbalance it. The actual torque generated by the linear actuator, T_actuator, was also calculated by using the given force specifications from the linear actuator's manufacturer which was 1000 N.

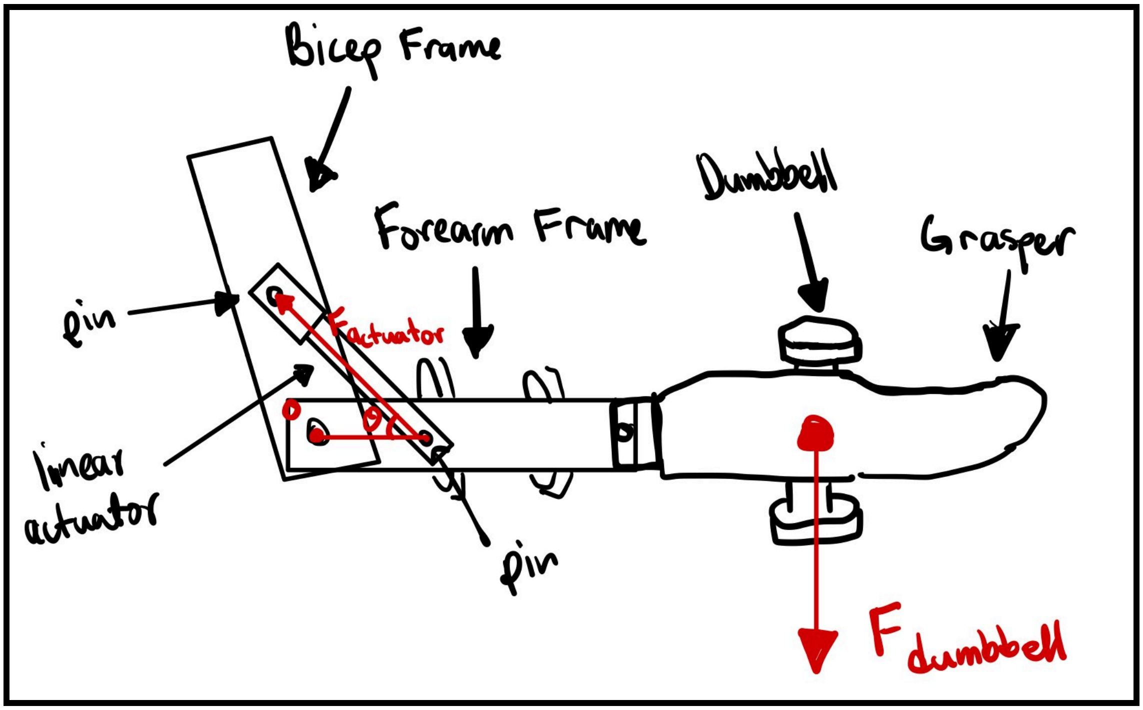


Figure 8: Calculator for Torque Generated by Dumbbell

Minimum Force to Lift Arm:

$$M_o(CCW + ve) = 0 = \tau_{actuator} - \tau_{dumbbell}$$

$$0 = (F_{actuator})(r_{actuator} sin\theta) - \tau_{dumbbell}$$

$$F_{actuator} = \frac{\tau_{dumbbell}}{r_{actuator}}$$

$$F_{actuator} = \frac{14.13\ N\cdot m}{(0.178\ m)(sin(12.9))}$$

$$F_{actuator} = 355.57\ N$$

Minimum Torque to Lift Arm:

$$\tau_{actuator} = \tau_{dumbbell}$$

$$\tau_{actuator} = 14.13\ N \cdot m$$

Actual Torque Generated by Linear Actuator:

$$\tau_{actuatorr_{actual}} = (F_{actuatorr_{actual}})(r_{actuator} sin\theta)$$

$$\tau_{actuatorr_{actual}} = (1000\, N)((0.178\, m)(sin(12.9))$$

$$\tau_{actuatorr_{actual}} = 39.74\, N \cdot m$$

These calculations show that the linear actuator used has more than enough torque and force to raise the arm.

Hand Grasper

Grasper Frame:

The grasper frame was created by measuring the demonstrator's hand and adjusting dimensions accordingly to ensure that the fit would be correct. This included measuring the demonstrator's arn from the wrist to the elbow joint, which was measured to be 260mm. From the wrist to the demonstrator's inner fist was measured to be 100mm. As such the distance from the bolts joining the forearm frame and the grasper frame were adjusted so that the handle was 100mm from the bolts which are located at the wrist. This ensured a good fit for the demonstrator. We also had to ensure that the grasper frame could be printed in the 3D printer, meaning it would need a size of 256x256x256mm or less.

Grasper Jaws:

The two jaws on the hand grasper were created by ensuring that they would be 3D printable, so 256x256x256mm or less, and also by ensuring that the jaws converged at the centerpoint of the hand grasper. This would enhance the ease of use for the user. There is also a 2nd set of smaller jaws protruding from the large jaws which were created for demonstration purposes. The smaller set of jaws were designed such that a dumbbell of diameter 30mm could be gripped easily for demonstration. A more robust jaw for different scenarios could be easily created. A locking mechanism was also designed to lock the jaws if they are under heavy load which involves placing a pin inside a hole which joins the large left and right jaws together.

Handle:

A robust and ergonomic handle was created using splines which was an improvement from the first iteration which had an unergonomic cylinder as the handle. The handle features a hole down the center of it which is pinned to the grasper frame and allows for rotation. A protrusion has also been created on the top of the handle for attachment of a wire which is detailed in the grasper jaw mechanism section.

Grasper Jaw Mechanism:

Protrusions were made in the handle and left jaw of the hand grasper to fit a wire which would allow the handle to act as a pulley. This would let the jaw mechanism open if the handle is rotated forwards. Modelling the wire in NX proved difficult and it was decided to omit it from the model as the motion sim already modelled the mechanism effectively.

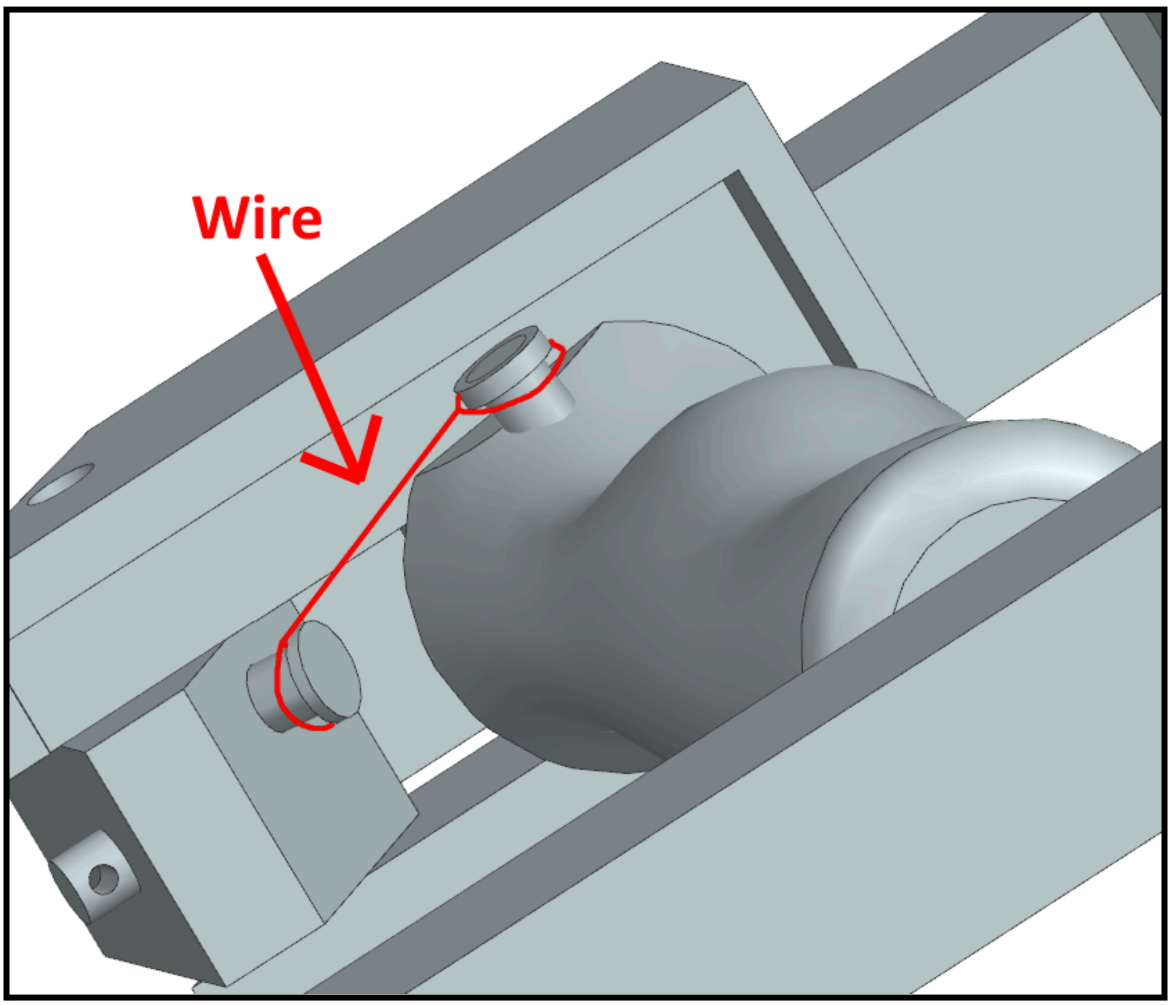


Figure 9: Handle Pulley Mechanism

The handle pulley mechanism was responsible for opening the jaw, but another mechanism was needed to close the jaw. To accomplish this task, we decided to implement a spring that would keep the jaw closed until the handle is rotated forward, which would allow the user the open the jaw by closing the handle and then the jaw would close when the user lets go of the handle or returns the handle to it's original position. The mechanism is shown in the figure below.

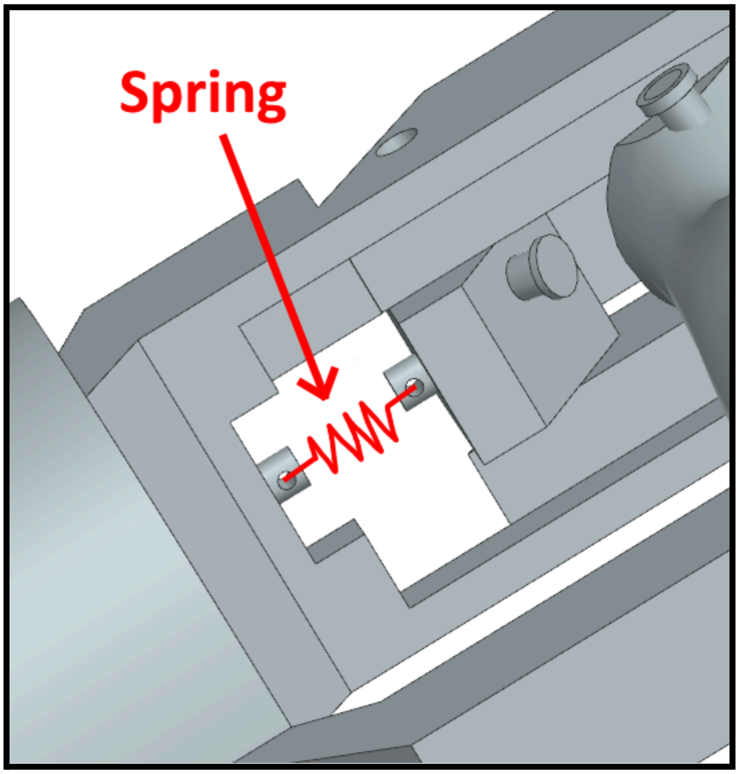


Figure 10: Spring Mechanism

The spring would be vulnerable to being 'pried open' under the weight of a load picked up by the jaws if it was in a vertical orientation, so the k constant would need to be high. As such, the k constant was calculated to determine what spring constant would be needed. The torque of the dumbbell was found and used to find the spring constant. X, or the distance between the ends of the spring, was measured to be 1.7cm.

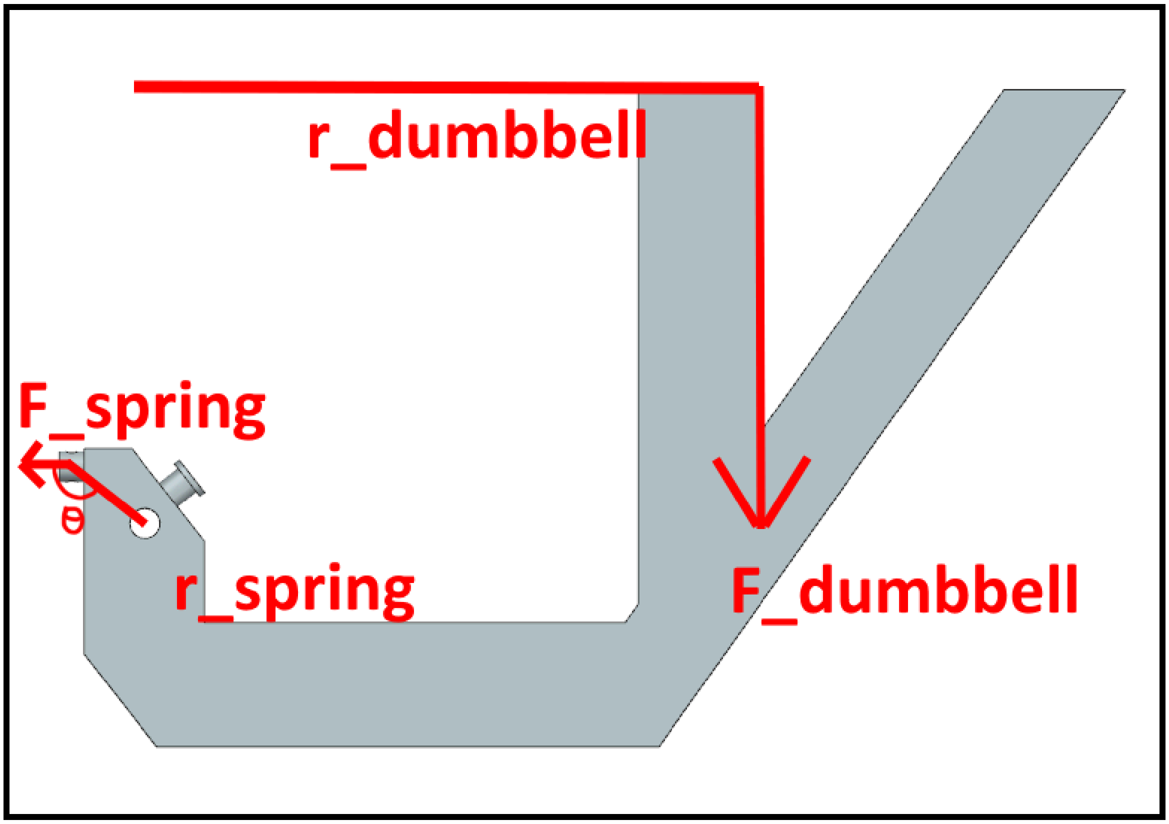


Figure 11: Free-Body Diagram of Left Jaw under Load of Dumbbell in Vertical Orientation

Force Exerted by Spring:

$$M_o\,(CCW\ +ve)\ =\ 0\ =\ \tau_{spring} - \tau_{dumbbell}$$

$$\tau_{spring} = \tau_{dumbbell}$$

$$(F_{spring})(r_{spring})\ =\ (F_{dumbell})(r_{dumbbell)})$$

$$F_{spring} = \frac{(F_{dumbell})(r_{dumbbell)})}{(r_{spring}sin(\theta))}$$

$$F_{spring} = \frac{(44.145\ N)(0.133m)}{(0.0152)(sin(37.8))}$$

$$F_{spring} = 630\ N$$

Spring Constant:

$$F_{spring} = \; -Kx$$

$$K = -\frac{F_{spring}}{x}$$

$$K = -\frac{630\ N}{-0.017\ m}$$

$$K = 37\ kN/m$$

The spring constant prove to be extremely high due to the short lever of the spring and the much larger lever of the dumbbell. To remedy this problem, pins were designed at the top of the jaws to lock them into place when they undergo heavy loads.

Parametric curves greatly benefited the Exomen arm, especially the handle. Parametric curves increased user comfort and aesthetics.

Back Brace

The back brace was designed to stay snuggly on the users and provide load carrying capabilities to the user. The arm loops ensure that the back brace doesn't fall off the user. The loops were designed by measuring the demonstrator's arm diameter and ensuring that the specified diameter would be able to fit through the loop. The gap between shoulder plates on the back brace was designed by measuring the demonstrator's head size and ensuring that it had sufficient clearance to fit around the demonstrator's neck and head. The back brace was also initially too big to 3D print, so it was broken up into smaller pieces with connections to attach them after. These connections were then further strengthened by applying superglue.

Back Brace to Bicep Frame Connector

The Back Brace to Bicep Frame Connector provided a rigid connection between the back brace and bicep frame. It was pinned at both ends, which allowed the Exomen arm to perform shoulder flexion. The radius of the connector was found by measuring the demonstrator's shoulder and ensuring that the radius was sufficiently large enough that there would be no collision between the connector and the demonstrator's shoulder.

Risks and Safety

To ensure safety and mitigate risk of components breaking as this device would be worn by a customer, we made sure that no component had a safety factor below 1.5 [4] in this project.

Initially there were 3 rings in the forearm frame, with one being at the connection between the forearm frame and hand grasper, one being near the end of the frame, and one being the middle. After further design evaluation, the last ring at the end of the frame was removed due to safety concerns of the ring colliding with the user's bicep or with the bicep frame.

The linear actuator was analysed very carefully for safety as it could produce immense pulling forces of up to 1000 N. We choose a linear actuator with a stroke of 50mm to ensure safety of the user. We chose a linear actuator with a stroke length of 50mm because it won't allow the forearm to reach a critical position where the forearm frame is collinear with the bicep frame and pull the forearm frame along the same axis as the bicep frame. Our placement of the linear actuator made sure that this was not a possibility. We also made sure to give ample clearance between the bicep frame and forearm frame rings so that when the linear actuator is fully retracted, there is no collision between any parts or collision between parts and the demonstrator's arm. For safety reasons, users shouldn't use the Exomen arm while wearing a long-sleeved shirt/hoodie as the fabric could be caught and pinched between the parts that revolve around the "elbow" joint.

The sharp edges around the bicep and forearm frame and ends of bolts sticking out were problematic as they could scrape the user's skin. To remedy this, fabric was applied to the inner part of the rings to cover any sharp edges and bolts, and it also increased comfort.

Fillets and chamfers were also used to round off any sharp edges that might have injured the user. For example, the end of the handle in the hand grasper was filleted and the left jaw was chamfered at an area where contact with the user's hand may be possible.

2. Design Analysis Documentation

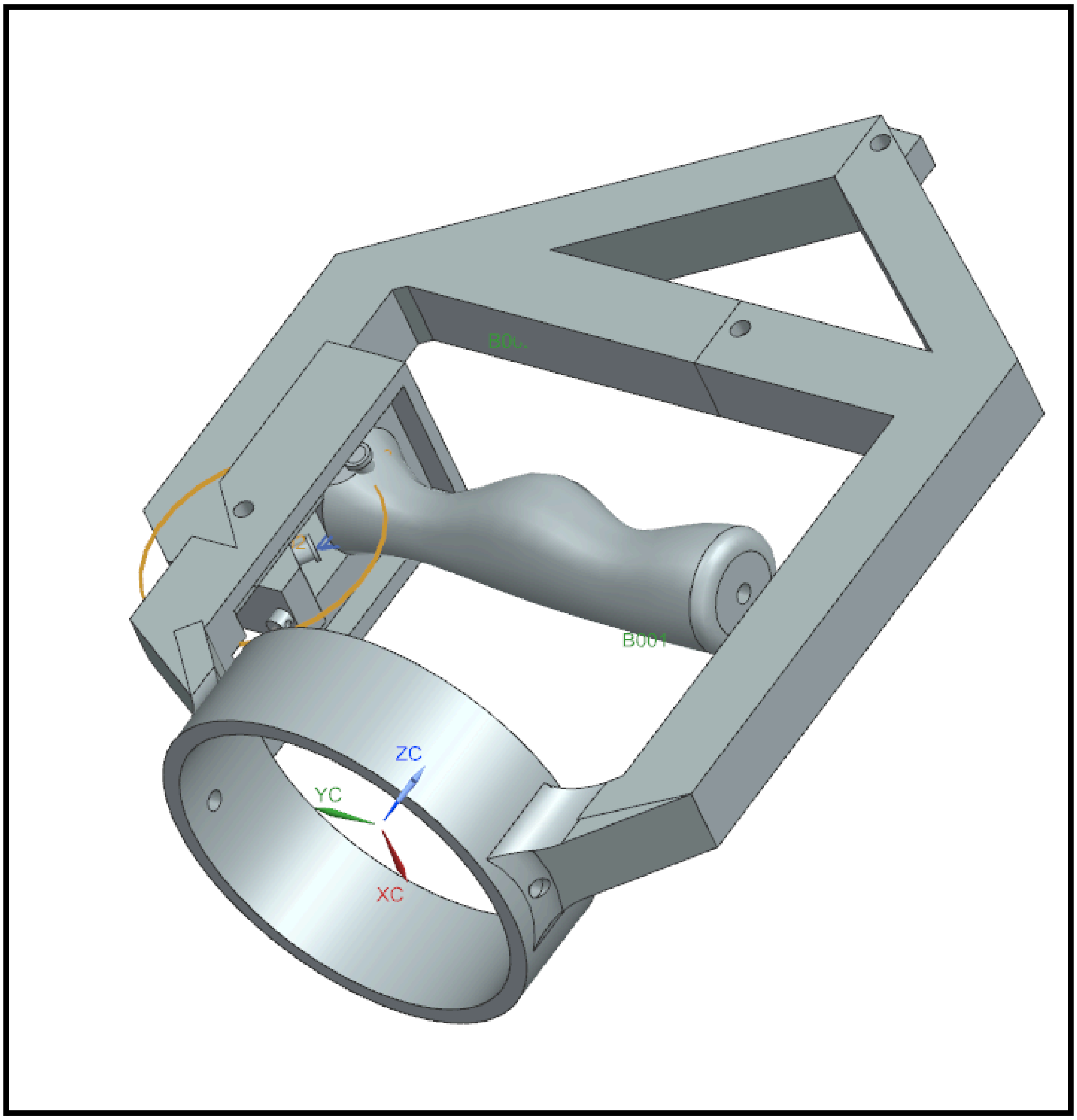


Figure 12: Closed Position of Hand Grasper Mechanism

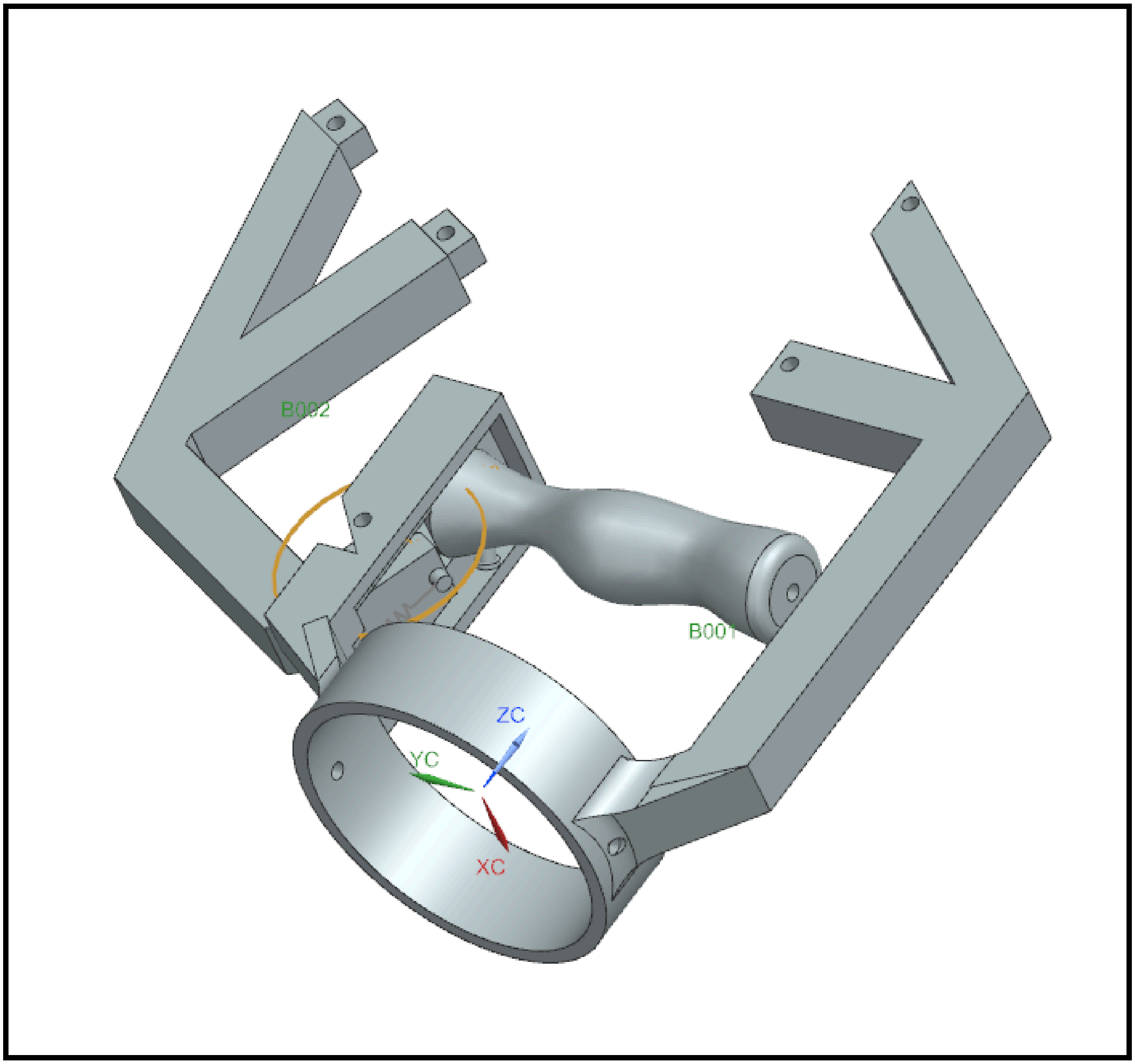


Figure 13: Open Position of Hand Grasper

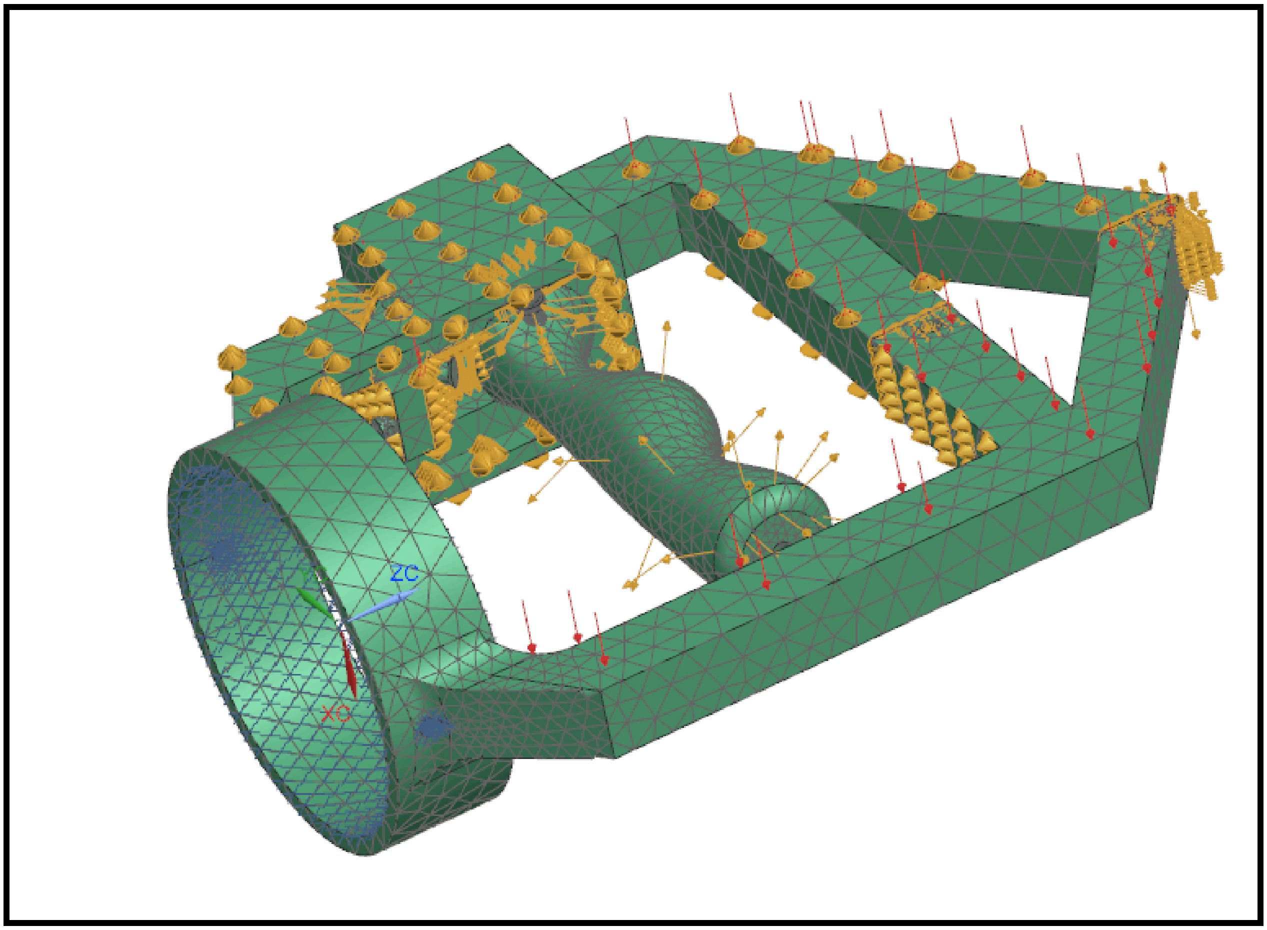


Figure 14: FEA Configuration of Grasper for 10lb Force Analysis

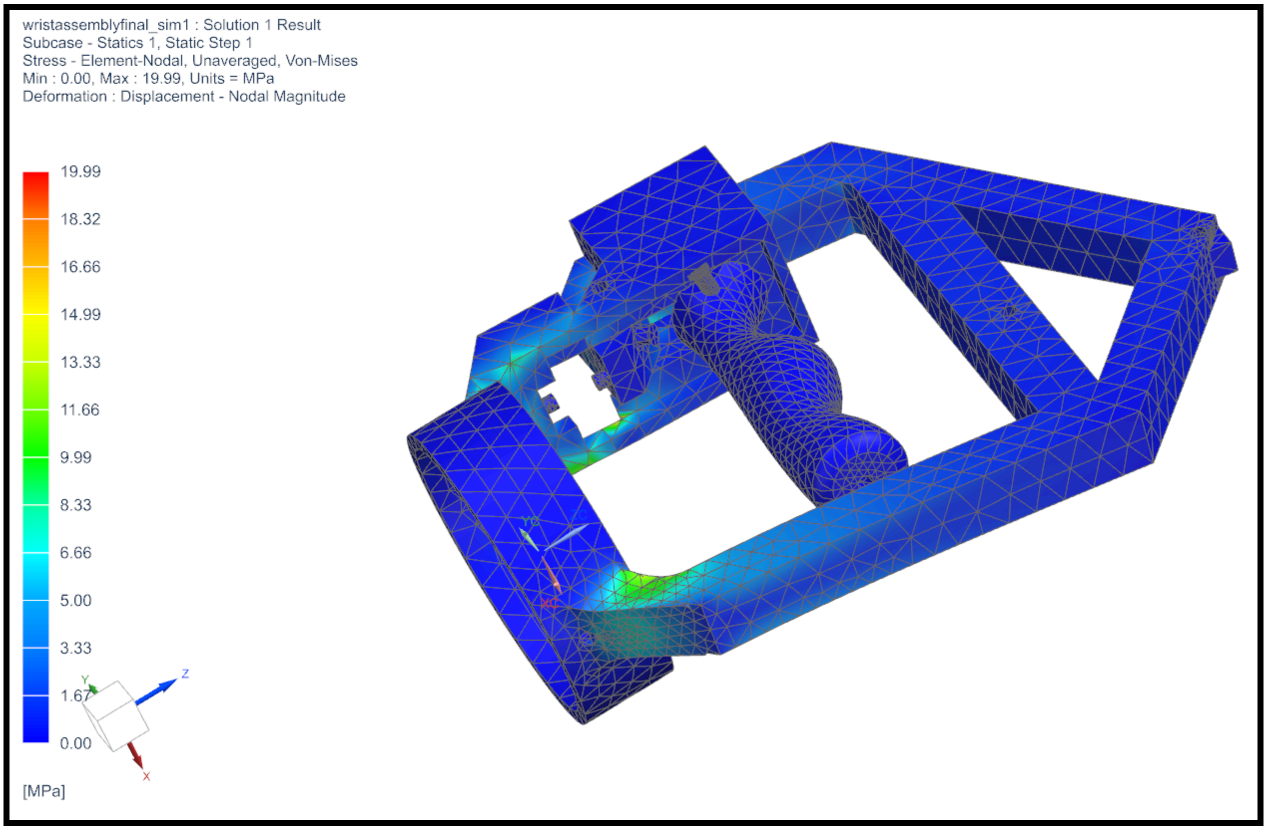


Figure 15: Element-Nodal Stress with 10lb Force Acting on Grasper Jaw

Yield stress of PLA is estimated to be 77 MPa, so this analysis indicates a safety factor of 3.85 in the high stress zones which is acceptable.

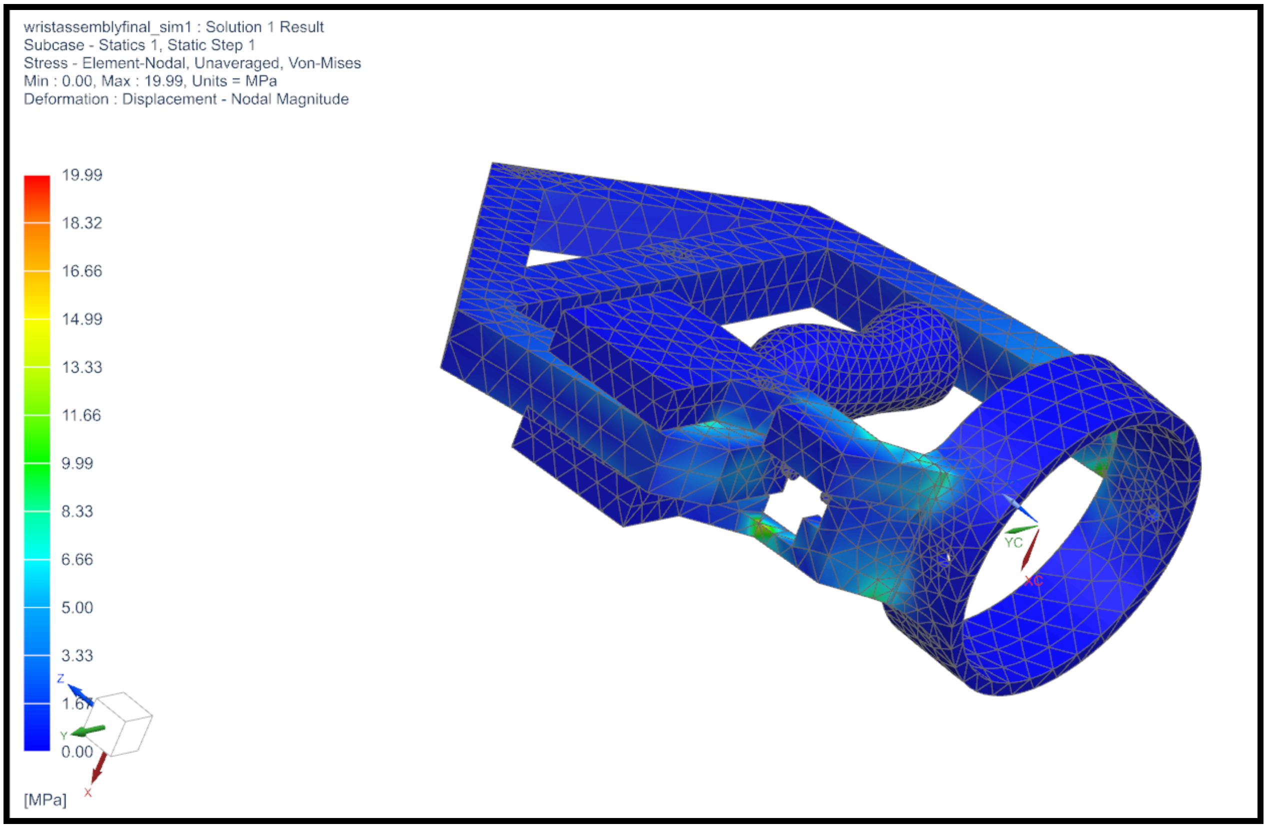


Figure 16: 2nd Angle of Element-Nodal Stress with 10lb Force Acting on Grasper Jaw

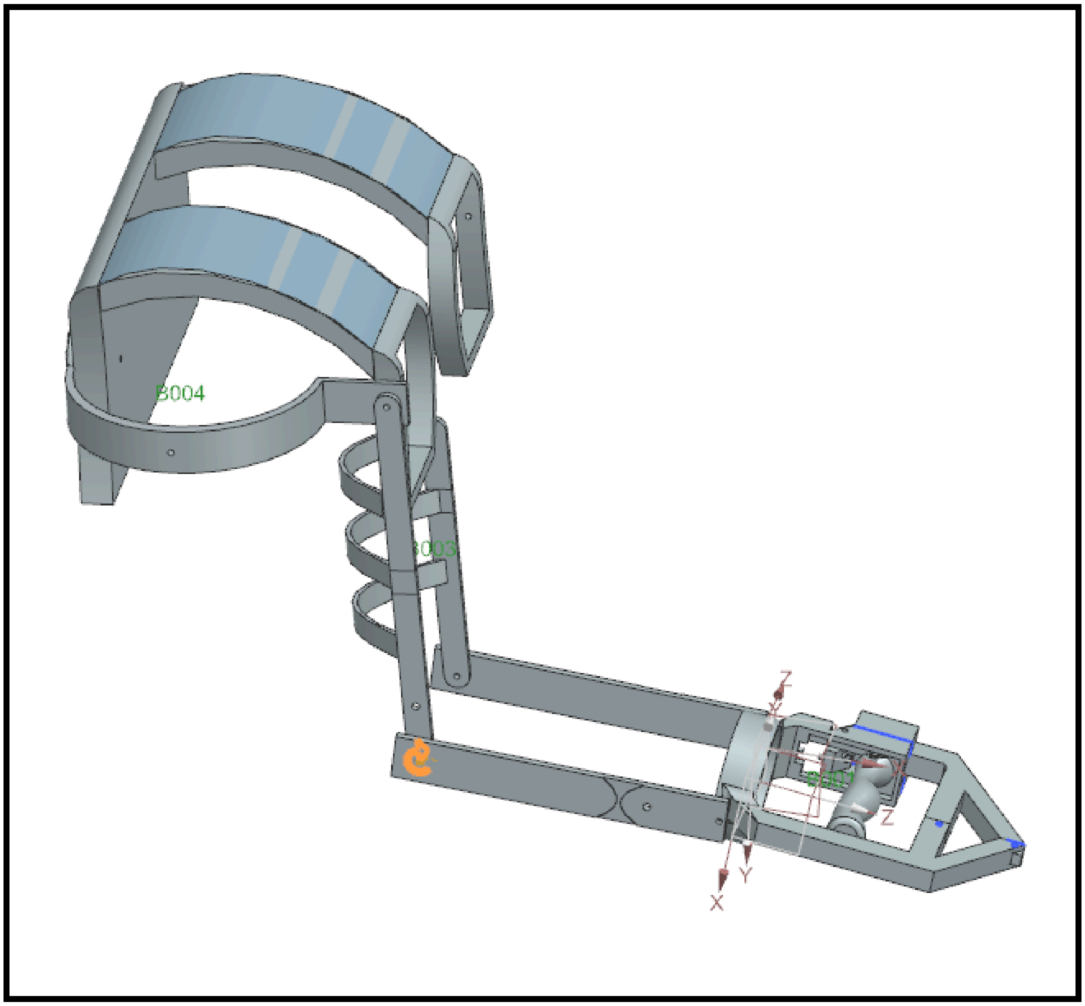


Figure 17: Extended Position of Exomen Arm (Bicep Flexion)

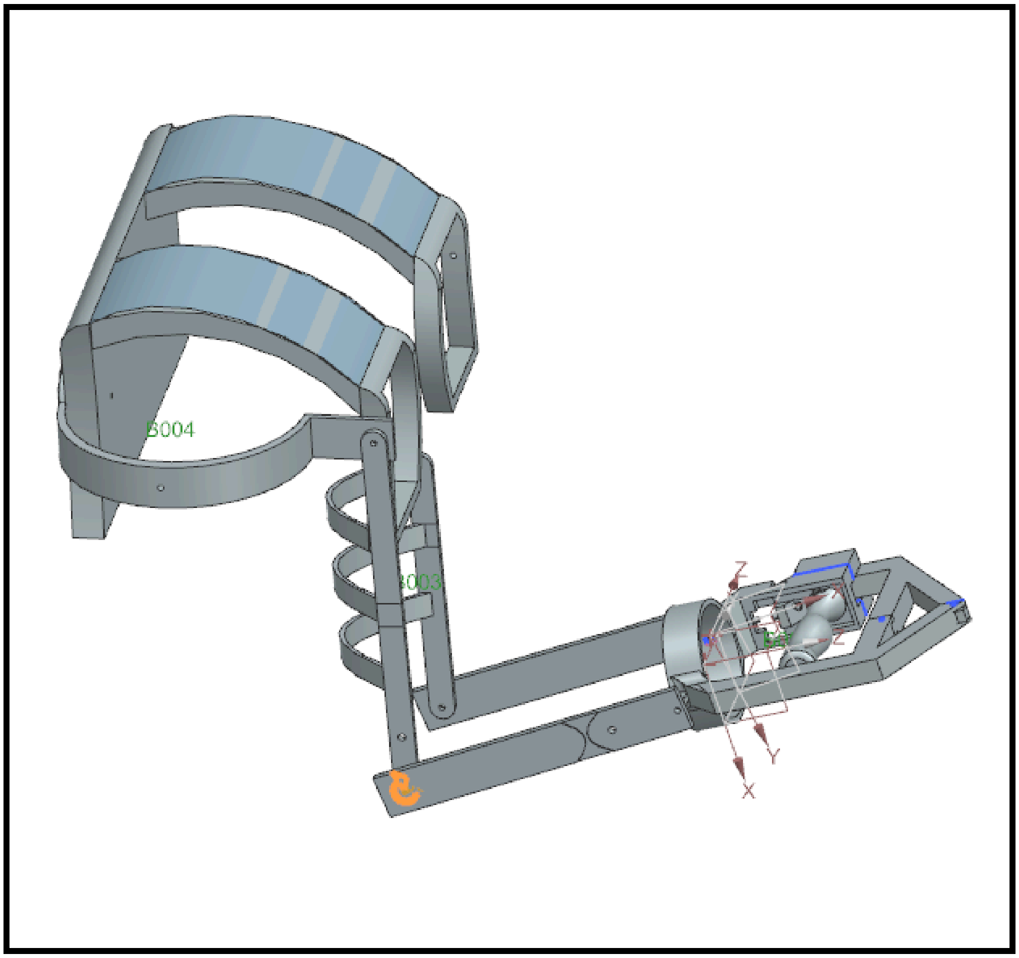


Figure 18: Retracted Position of Exomen Arm (Bicep Flexion)

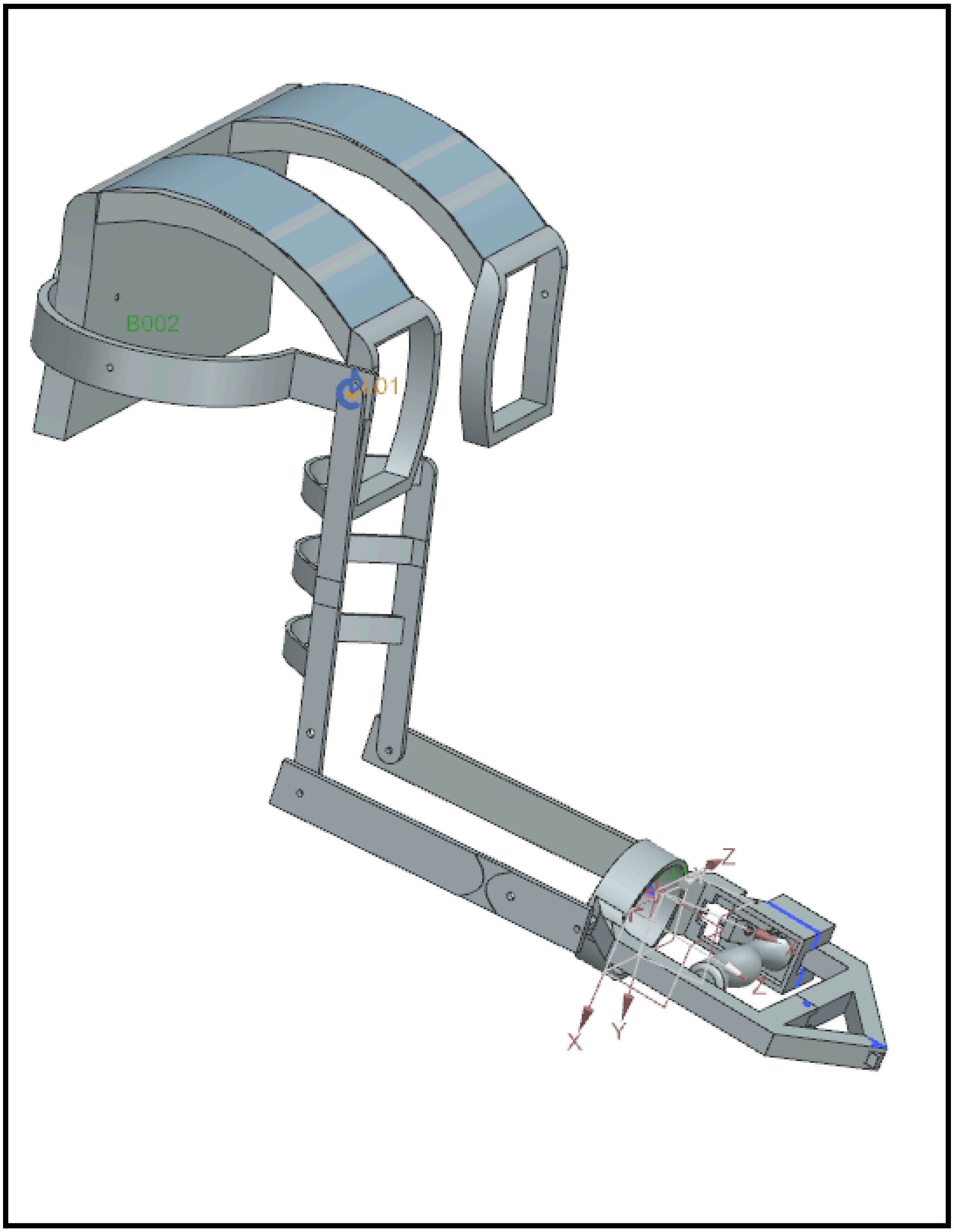


Figure 19: Retracted Position of Exomen Arm (Front Raise)

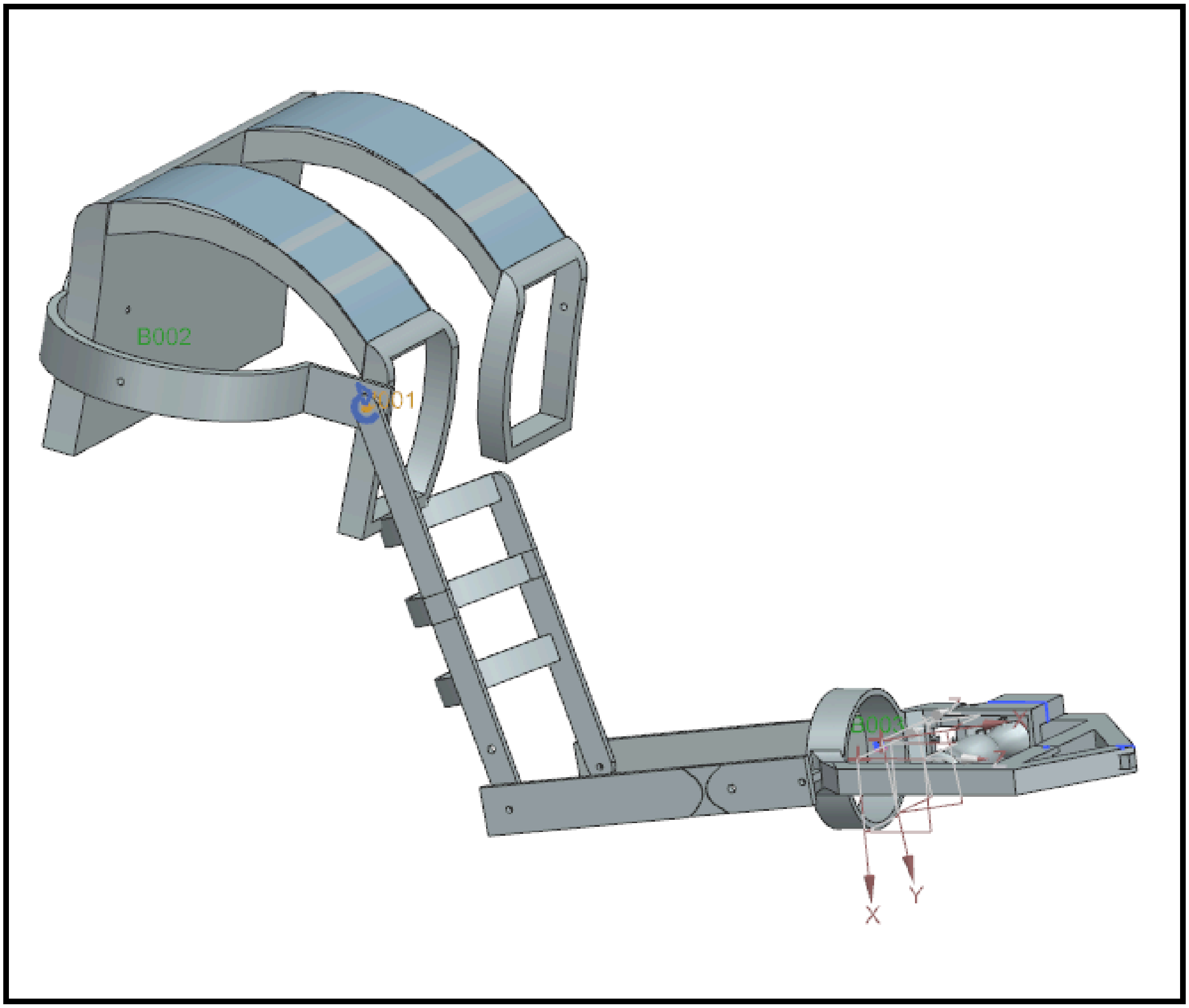


Figure 20: Extended Position of Exomen Arm (Front Raise)

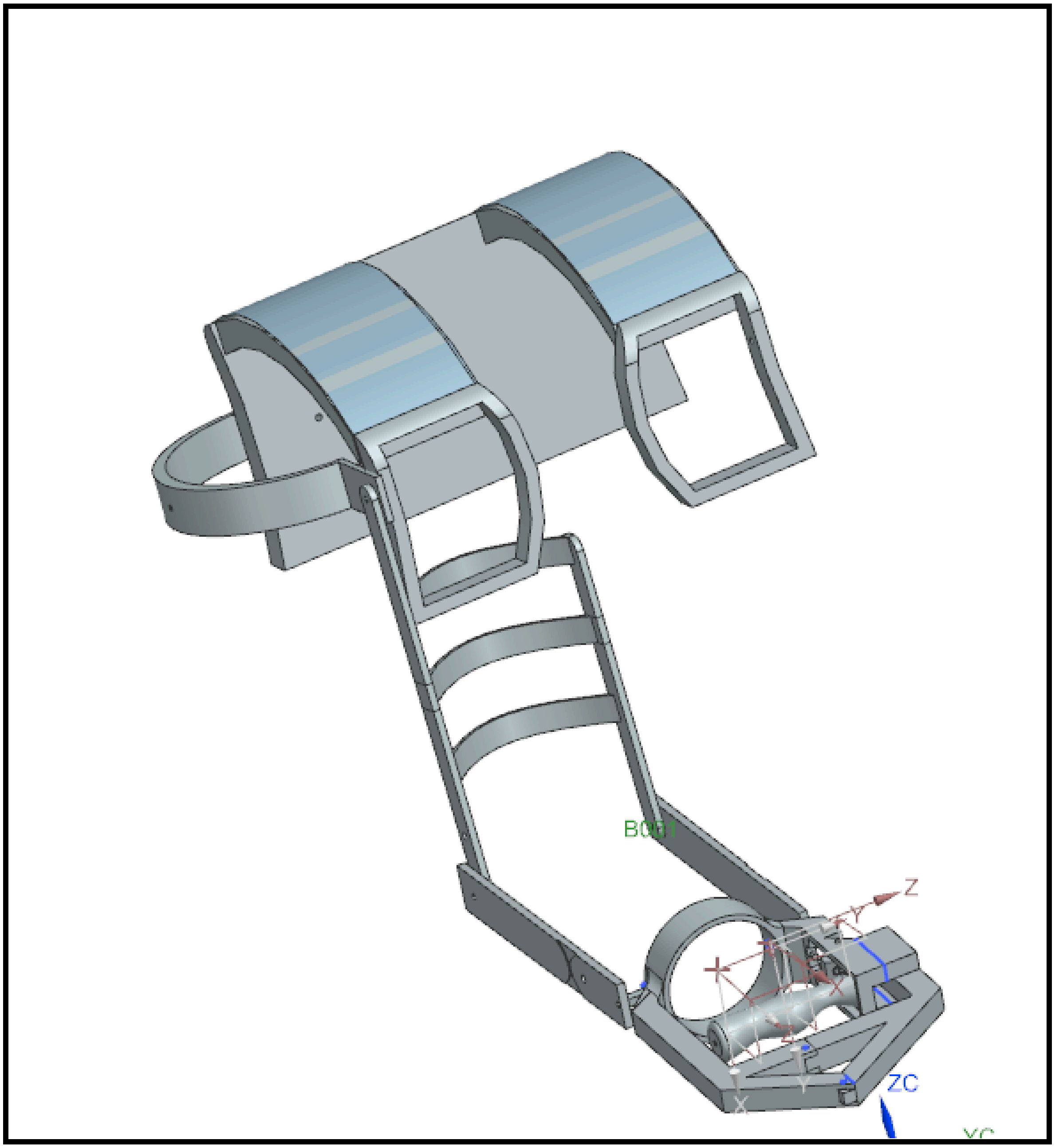


Figure 21: Retracted Position of Exomen Arm (Lateral Shoulder Flexion)

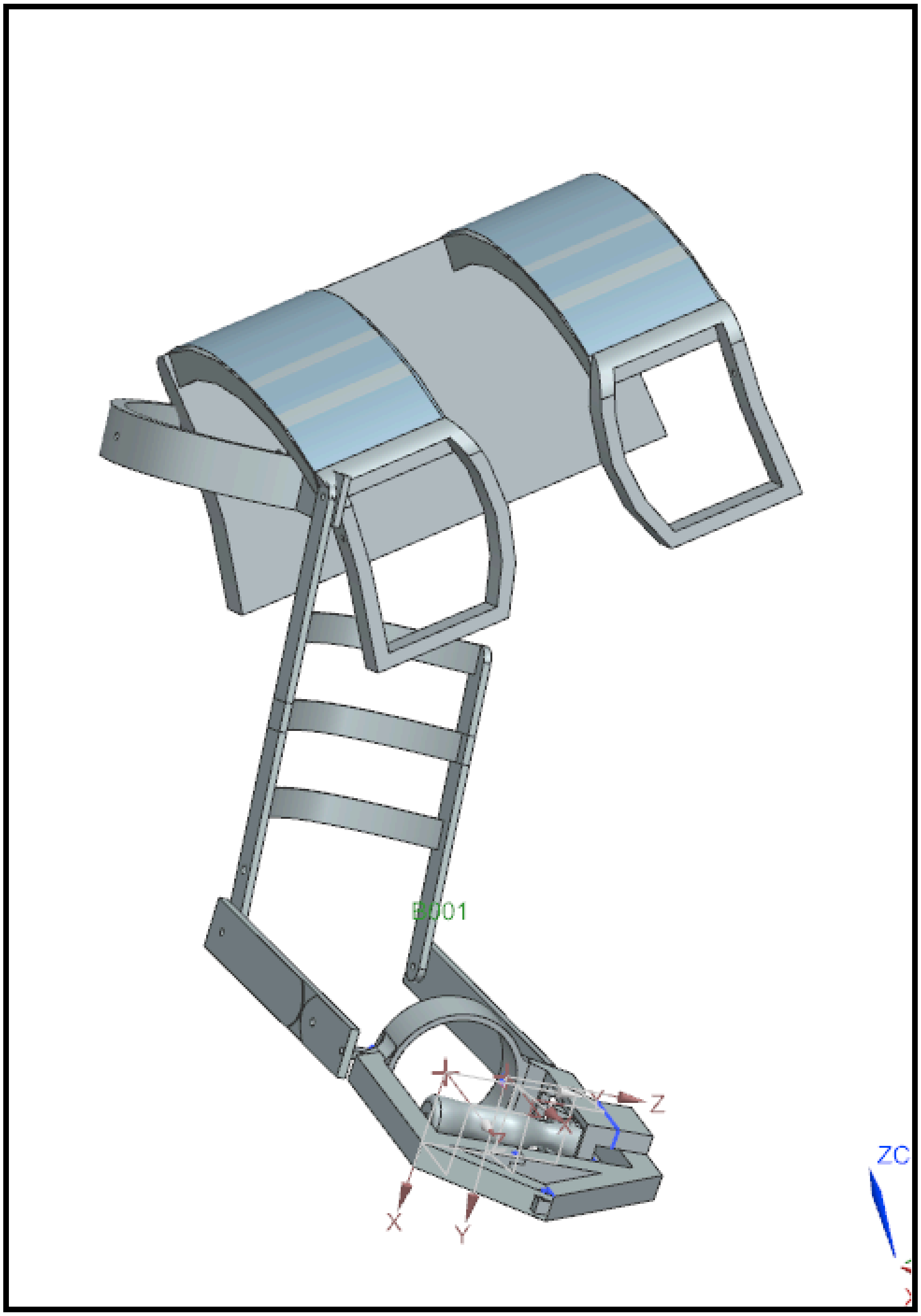


Figure 22: Extended Position of Exomen Arm (Lateral Shoulder Flexion)

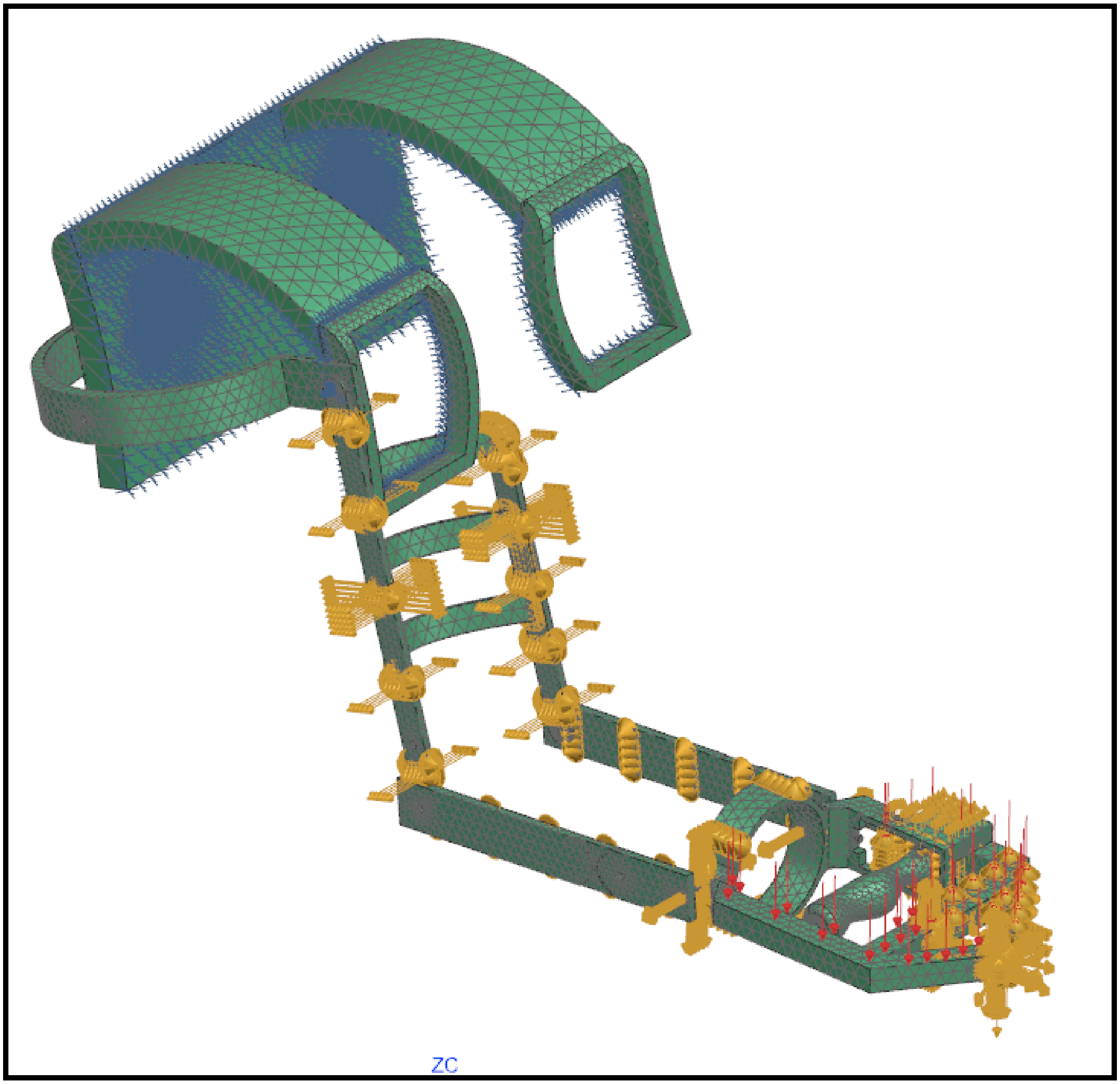


Figure 23: FEA Configuration of Exomen Arm for 10lb Force Analysis of Static Hold

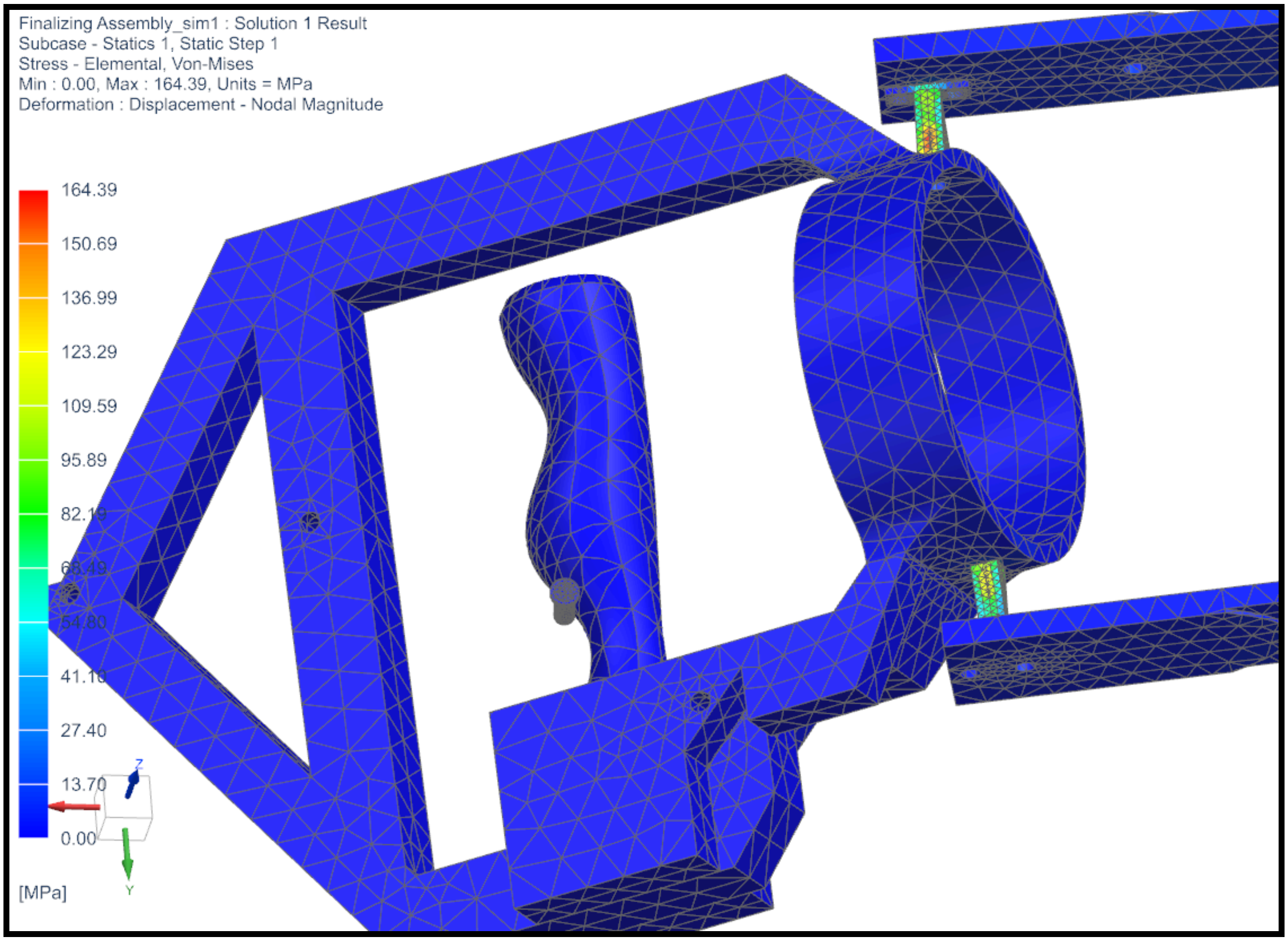


Figure 24: Element Stress with 10lb Force Acting on Exomen Arm under Static Hold

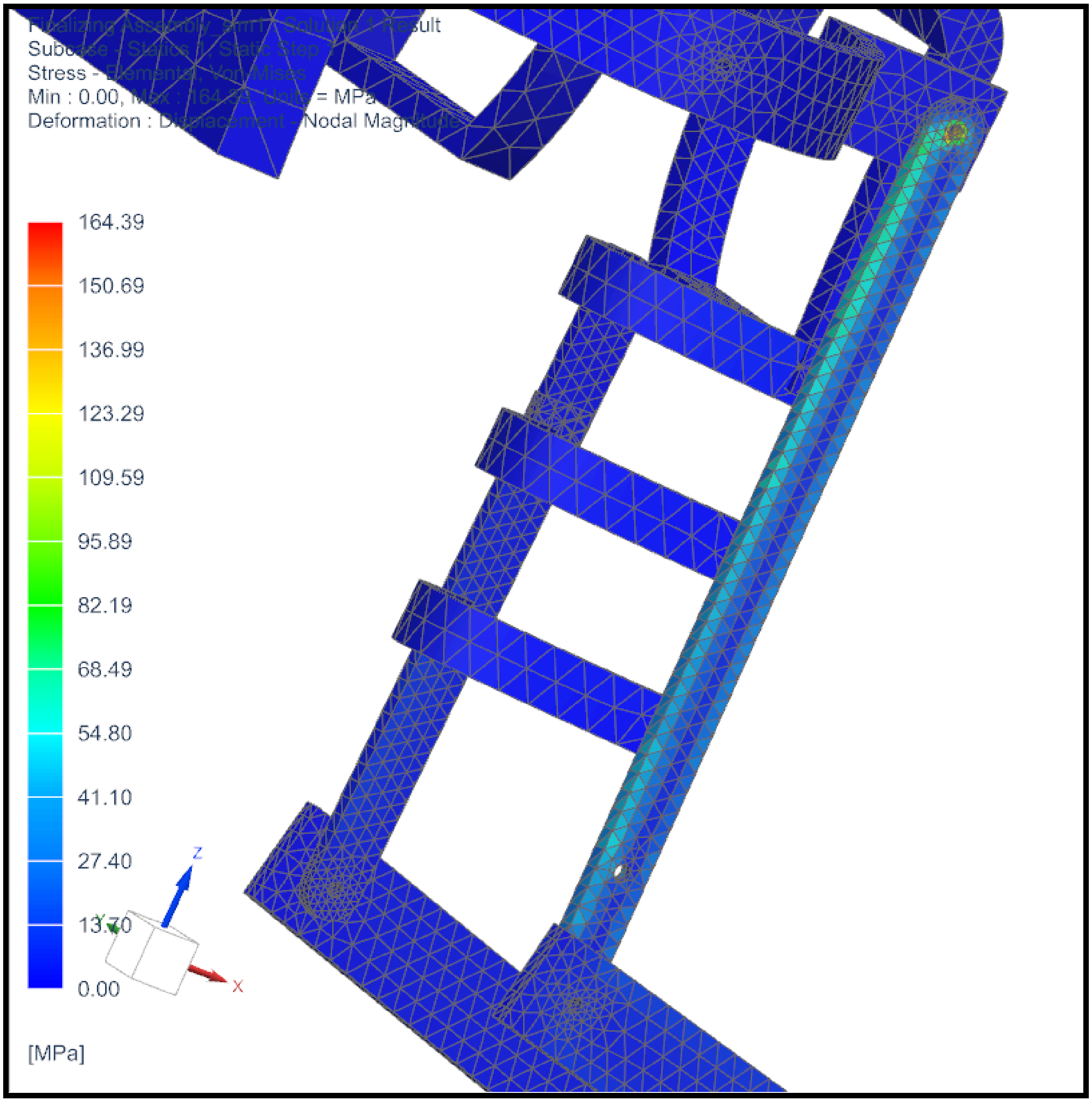


Figure 25: 2nd Angle of Element Stress with 10lb Force Acting on Exomen Arm under Static Hold

How the joints and drivers for the motion analysis were chosen

The goal of mimicking the human arm's natural range of motion while maintaining stability and load support influenced the team's choice of joints and drives significantly. To simulate bicep flexion, a rotational joint was used for the elbow joint, enabling the controlled lifting of large objects. Due to their dependability, robustness, and simplicity, linear actuators were selected as the drivers. The bicep flexion mechanism relied heavily on its capacity to deliver steady, regulated action. Furthermore, the shoulder's rotating joints supported weight distribution and guaranteed smooth shoulder motion.

How the boundary conditions and forces/torques were chosen

For the team to replicate real-world situations where the exoskeleton was required to lift big objects, boundary constraints were selected. For there to be a stable attachment to the body. The user's torso was fixed to the back brace's base. Forces and torques were applied at critical points, such as the wrist and elbow, to evaluate the device's response under load. To make sure the linear actuator could counterbalance this weight, the torque produced by a 4.5 kg dumbbell at the forearm's end was determined using the formula $\boldsymbol{\tau = r \cdot F \sin\theta}$.

Interpretation of results from motion analysis, FEA, and design iterations

Smooth motion of the elbow and shoulder joints were demonstrated within the motion analysis, confirming that the selected joint configurations permitted normal arm movements. Depending on how the load was distributed among polylactic acid components (PLA), the hand grasper's FEA findings indicated acceptable safety factors between 2.5 and 10. The grasper's jaws were found to have high-stress zones, which were reduced by strengthening and adding more material density. To guarantee that there were no accidents throughout full range-of-motion testing, boundary conditions in the arm's bicep frame were also improved.

Validation of the prototype structural integrity, range of motion, and force assistance capability

- **Structural Integrity:** The PLA 3D-printed grasper and aluminium arm frame, two of the prototype's structural elements, were verified to support the expected loads.
- **Range of Motion:** The exoskeleton demonstrated its was able to replicate natural human movements by allowing complete elbow and shoulder motion without any unwanted contact between parts.
- **Force Assistance Capability:** Torque calculations and practical testing verified that the linear actuator supplied enough force to raise a 4.5 kg dumbbell, demonstrating the device's effectiveness for lifting duties.

Comparison of results to motion analysis and FEA

The motion analysis results were similar to the FEA results. Regions of higher load visible in the motion analysis corresponded with high-stress areas found in the FEA. This correlation indicated some places requiring minor reinforcements, confirming how well the design was able to distribute forces throughout the exoskeleton. In order for the team to increase the design's durability and safety, some modifications were made, including filleting sharp edges and strengthening important stress points. These assessments made sure the exoskeleton design was affordable and comfortable for users while still meeting safety and functional standards.

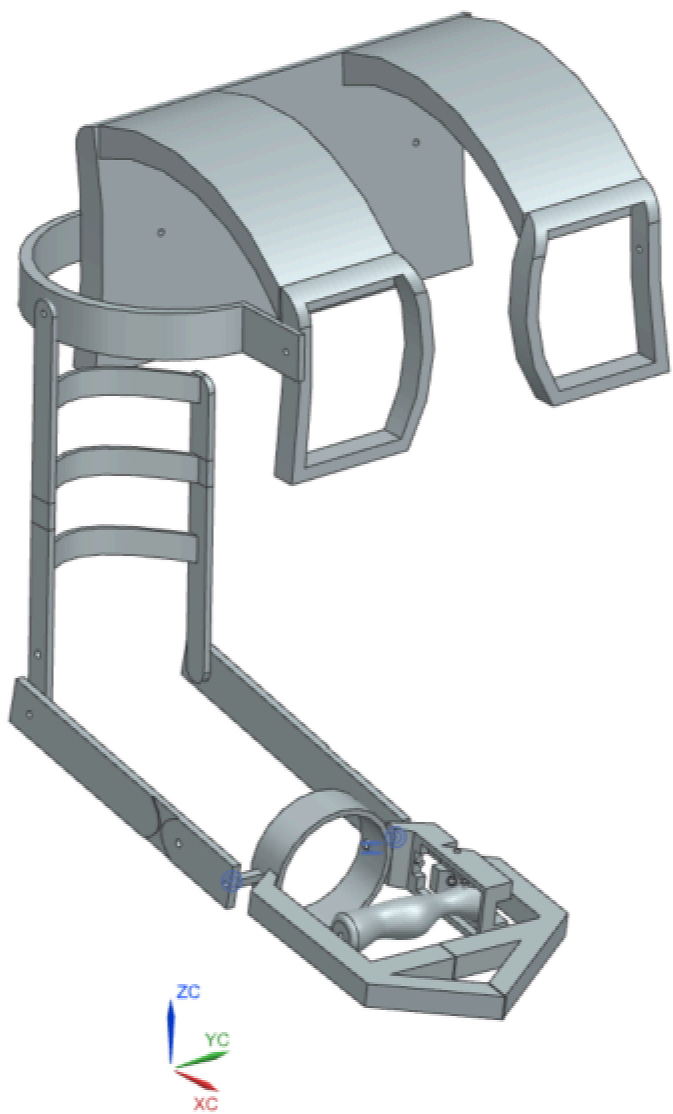


Figure 26: Full Assembly of the Worn Parts of the Exoskeleton

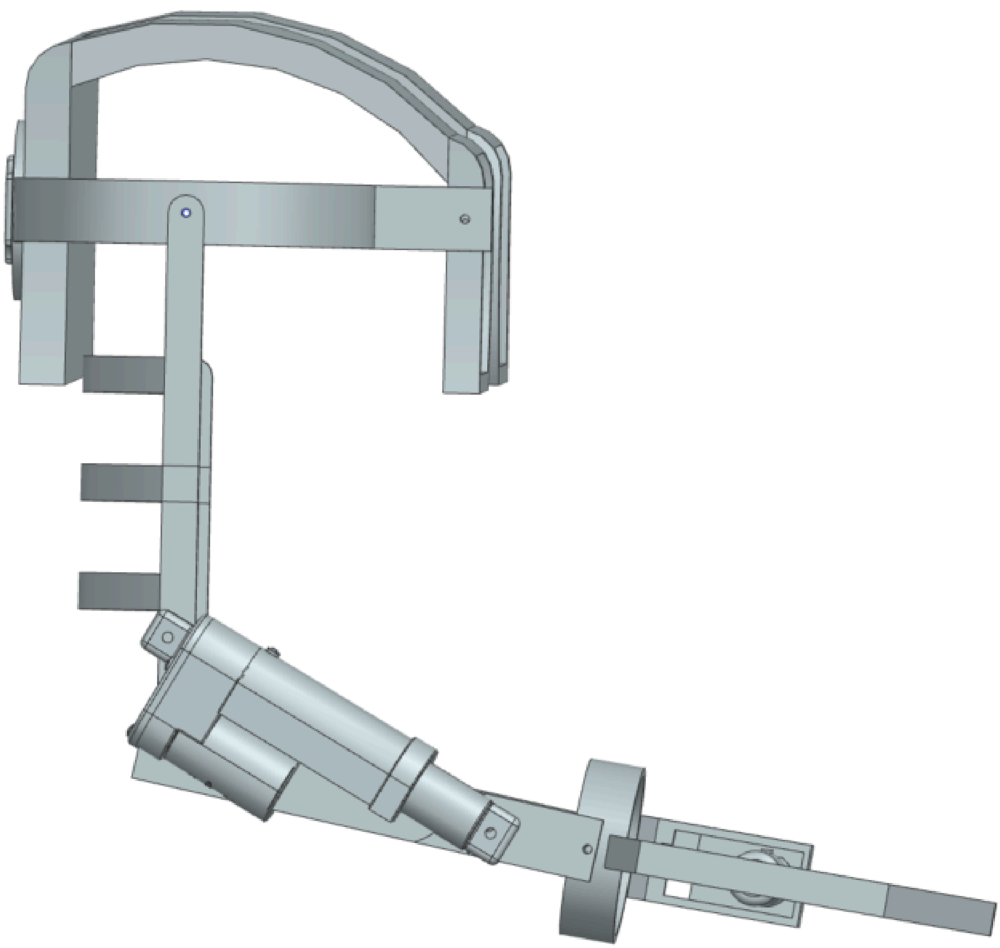


Figure 27: Full Assembly Including the Linear Actuator Which will be Added for the Demo in Order to Improve Functionality and Load Capacity.

3. Economic Analysis:

CAM and Manufacturing Process:

The exoskeleton is made up of 3D printed PLA as well as low grade aluminium steel. These come together with fasteners such as bolts, springs and nuts, to make the entire structure of the exoskeleton. The claw contains a strong spring to help move the claw. A switch is implemented on the arm to move a linear actuator which is attached to the arm. Starting with the back brace, it is entirely 3D printed PLA with 50% infill to ensure solid support as this will be connected to the straps as well as the heavier metal arm guard and claw. For the manufacturing process, the aluminium pieces will be purchased from metal distributors and cut accurately to size and shape using a cnc machine. Furthermore the specifics of the parts of the exoskeleton will be made with the lowest tolerance possible . The metal pieces will then be fastened using bolts, depending on the size. For the exoskeleton to be useful, it is crucial that this appeals to anyone's shoulder and arm size, therefore custom orders of different sizes can be made. The linear actuators and switches are purchased from 3rd party distributors, which are then attached in the factory.

The arm claw and handle contains complex geometry as the user will have to pull a lever to make the hook function appropriately. Which is why the 3D printing machine will print these with high infill density. Most of the complex geometrical shaped parts will be 3D printed using high quality PLA and high density, making the cost of each fully assembled exoskeleton less costly. Making the aluminium and the manual labour cost making up most of the cost.

Cost Analysis:

As mentioned below, the total cost of materials for a single exoskeleton comes up to $161.68. The manual labour costs are not too high, since only a couple things need to be fastened together using bolts. The main costs are from the 3D printing as most of the parts will be originating from that. There will be 4 separate 3D printers used to mass produce each part of the exoskeleton such as the back strap, the connectors for the arm, the back brace as well as the front strap. These approximately will cost 10 dollars per day per machine. Running 4 would cost 40 dollars a day. Which may not seem like a lot however in the long run, may affect the price to performance ratio a little. For the medium CNC machine used, it would approximately cost 5 dollars a day, without considering maintenance to run the machine for minimum 6 hours a day. Shipping will be international to any part of the world, and half of the shipping costs will be paid by the customer. All together each unit would cost $250 dollars plus shipping and taxes. A price considered to be reasonable, since the exoskeleton can be custom made if required.

Bill of Materials:

ITEM#	Component	Description	Unit Cost	Quantity	Total Cost
1	Switch/Toggle	Toggle Switch, 20A, 125VAC	$7.92	1	$7.92
2	Battery Holder	Battery Holder with switch, 2 AA battery holder, 3 pack	8.12 / 3 = $2.70	1	$2.70
3	1/4 bolts	1/4 * 1 - 1/2 inch hex head cap screw	$0.50	20	$10
4	12 * 12 inch aluminium	Low grade, non-heat treatable aluminium piece	$44	1	$44
5	Linear Actuator	DC12V 10 inch stroke linear actuator with mounting bracket	$42.99	1	$42.99
6	Stainless Compression Spring	1" 302/304 stainless steel compression spring	$14.06	1	$14.06
7	PLA filament 1.75 mm, 1kg	3D printing PLA filament, 1.75 mm, 1KG, Filament accuracy +/- 0.02 mm	$20.00	2	$40.00
				Total	**$161.68**

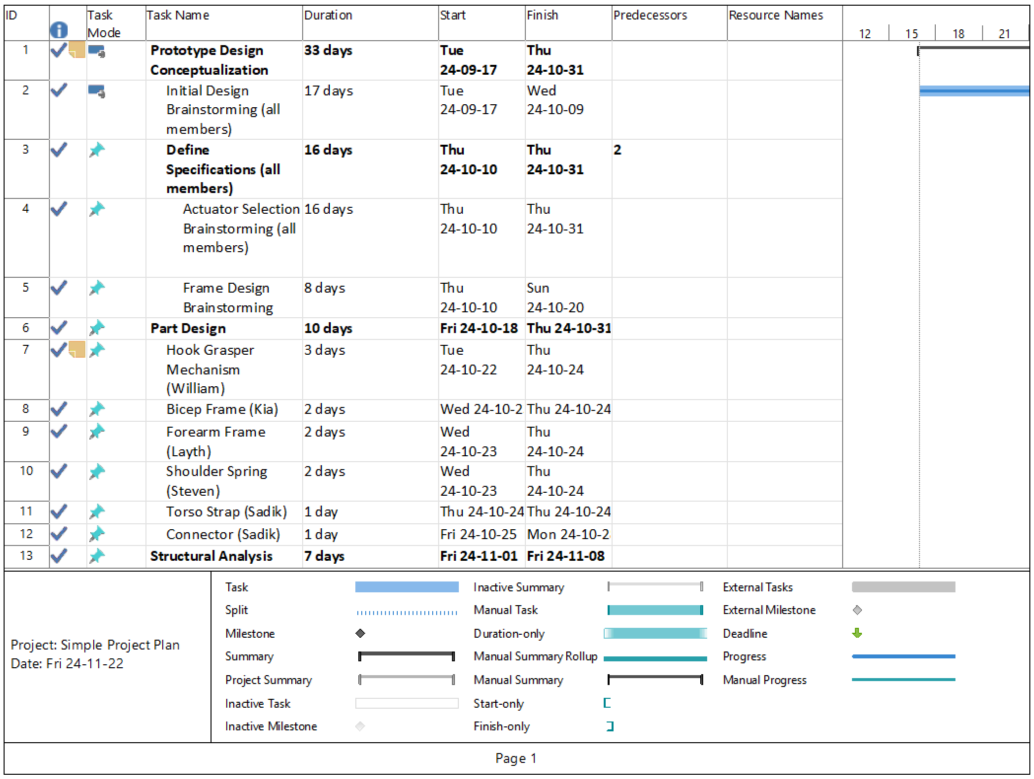
Figure 28: Bill of Materials

This is the price for one singular exoskeleton coming to a total of $161.68. The price is pretty average for each of the parts and can be assumed to be a reasonable figure. It is important to note as the material cost is low, the labour cost will be high for the physical construction of the exoskeleton as well as the electricity used by the 3D printer and its maintenance; to constantly print the parts required.

Manufacturing Process Planning for Large-Scale Production

For large-scale production of the exoskeleton, the manufacturing process will focus on efficiency, cost reduction, and maintaining quality. Structural components will be made from 6061-T6 aluminium using CNC machining for precision and extrusion for standard profiles, while non-load-bearing parts will transition from 3D-printed PLA to injection-molded ABS plastic for durability and scalability. Injection molding, though requiring upfront tooling costs, will significantly lower per-unit costs in high-volume production. Automated assembly lines with robotic arms will handle tasks like fastening and actuator installation, while human labour will focus on final assembly and quality checks. To ensure safety and functionality, batch testing for load-bearing capacity, joint motion, and safety factors will be implemented. The purchase of materials and fasteners in bulk will help lower costs. Packaging will use recycled materials for sustainability, and global distribution will be streamlined through external shipping providers. With a projected unit cost of $150–$180, the exoskeleton can be competitively priced at $300–$350, balancing affordability with profitability. Scalability is ensured by adaptable tooling and increased automation potential for future demand.

4. Design Project Management



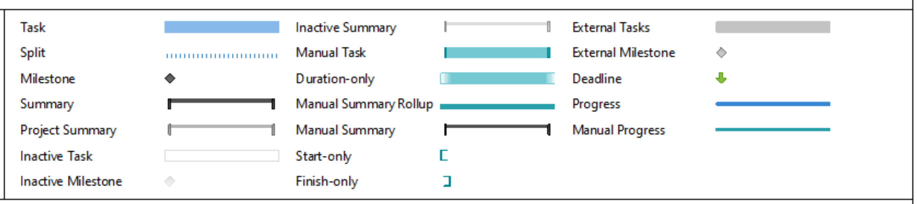
ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors	Resource Names
1		**Prototype Design Conceptualization**	**33 days**	**Tue 24-09-17**	**Thu 24-10-31**		
2		Initial Design Brainstorming (all members)	17 days	Tue 24-09-17	Wed 24-10-09		
3		**Define Specifications (all members)**	**16 days**	**Thu 24-10-10**	**Thu 24-10-31**	**2**	
4		Actuator Selection Brainstorming (all members)	16 days	Thu 24-10-10	Thu 24-10-31		
5		Frame Design Brainstorming	8 days	Thu 24-10-10	Sun 24-10-20		
6		**Part Design**	**10 days**	**Fri 24-10-18**	**Thu 24-10-31**		
7		Hook Grasper Mechanism (William)	3 days	Tue 24-10-22	Thu 24-10-24		
8		Bicep Frame (Kia)	2 days	Wed 24-10-2	Thu 24-10-24		
9		Forearm Frame (Layth)	2 days	Wed 24-10-23	Thu 24-10-24		
10		Shoulder Spring (Steven)	2 days	Wed 24-10-23	Thu 24-10-24		
11		Torso Strap (Sadik)	1 day	Thu 24-10-24	Thu 24-10-24		
12		Connector (Sadik)	1 day	Fri 24-10-25	Mon 24-10-2		
13		**Structural Analysis**	**7 days**	**Fri 24-11-01**	**Fri 24-11-08**		

Figure 29: Gantt Chart Pt. 1

ID		Task Mode	Task Name	Duration	Start	Finish	Predecessors	Resource Names
14	✔		FEA Analysis	2 days	Fri 24-11-01	Sat 24-11-02		
15	✔		Stress Testing	2 days	Sun 24-11-03	Mon 24-11-0		
16	✔		Motion Analysis	4 days	Tue 24-11-05	Fri 24-11-08		
17	✔		**Construction**	**7 days**	**Sat 24-11-09**	**Sat 24-11-16**		
18	✔		Metal Parts Manufacturing	3 days	Sat 24-11-09	Tue 24-11-12		
19	✔		3D Printing	3 days	Wed 24-11-1	Fri 24-11-15		
20	✔		Prototype Assembly	1 day	Sat 24-11-16	Sat 24-11-16		
21	✔		Report	6 days	Sun 24-11-17	Fri 24-11-22		
22			Project Due Date		Thu 24-11-21			

12 15 18 21

Project: Simple Project Plan
Date: Fri 24-11-22



Page 2

Figure 30: Gantt Chart Pt. 2

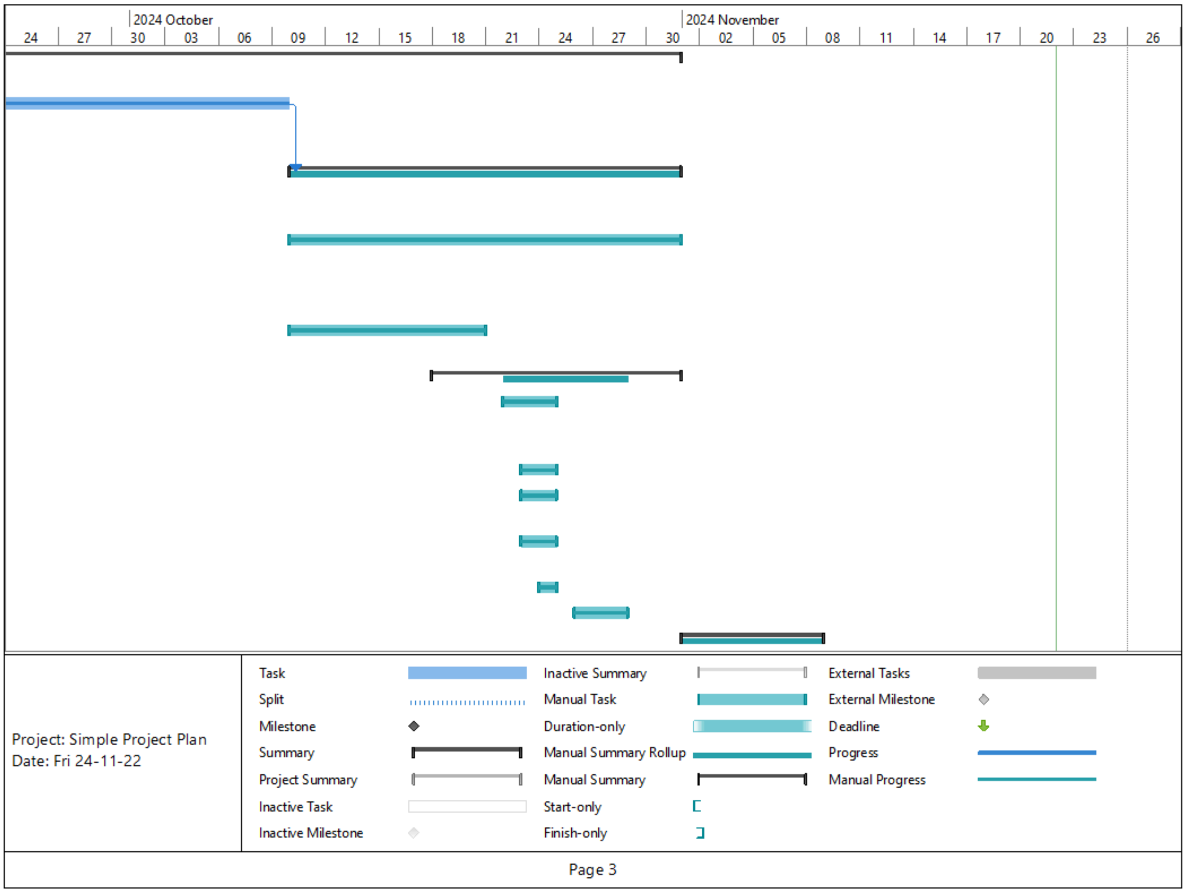


Figure 31: Gantt Chart Pt. 3

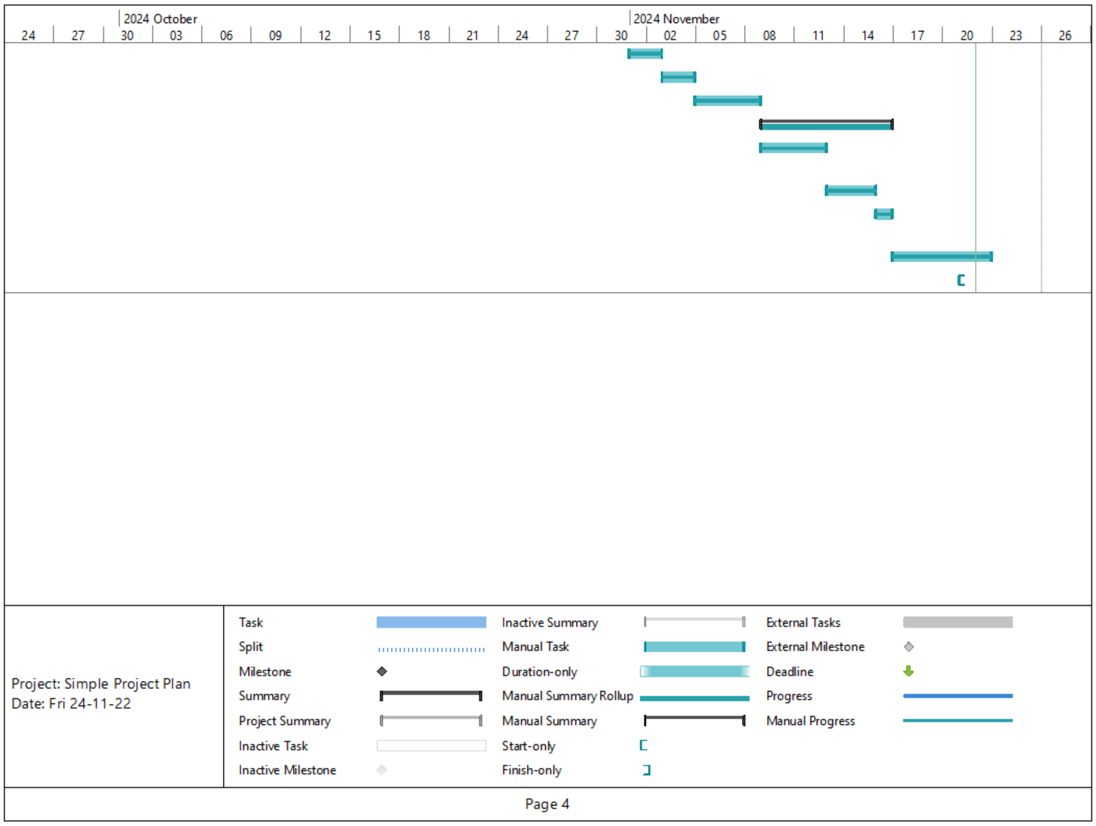


Figure 32: Gantt Chart Pt. 4

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[2] Lehman's, "Shoulder Yoke," Lehman's, n.d. [Online]. Available: https://www.lehmans.com/product/shoulder-yoke/lawncare. [Accessed: Nov. 11, 2024].

[3] GrabCAD, "Linear Actuator," GrabCAD, 2024. [Online]. Available: https://grabcad.com/library/linear-actuator-16. [Accessed: Nov. 19, 2024].

[4] SafetyCulture, “Factor of Safety,” SafetyCulture, 2024. [Online]. Available: https://safetyculture.com/topics/factor-of-safety/. [Accessed: Nov. 21, 2024].