Design and Development of an Artificial Pneumatic Muscle-based Exoskeleton System for Upper limb Rehabilitation

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Plan of Presentation

- Introduction
- Motivation and Objective of the Work
- Muscle Fabrication and Testing
- Implementation of PAMs on wooden Dummy
- Design of Exoskeleton
- Implementation of Exoskeleton on Human Arm
- Conclusions
- Scope for Future Work

Introduction

- Individuals facing upper limb paralysis or amputation encounter daily challenges, leading to dependency and psychological strain. Existing solutions, such as electromechanical exoskeletons, are often bulky and financially prohibitive.
- Pneumatic Artificial Muscles (PAMs) offer a transformative alternative. These lightweight actuators present a cost-effective option, making exoskeleton suits more accessible to a broader demographic.
- Our objective is to explore the potential of PAMs in designing affordable exoskeleton suits for upper limb rehabilitation. The benefits are twofold: enabling users to regain independence in daily activities and overcoming financial barriers through a more affordable technology.
- In conclusion, PAM-based exoskeletons hold promise in significantly improving the lives of individuals with upper limb challenges, fostering autonomy and mental well-being.

Motivation of the Work

- Based on the literature review, it is observed that pneumatic artificial muscles can be very well integrated with exoskeletons making it very light weight for the user.
- However, all the studies were primarily devoted to studying were primarily devoted to only study the mathematical models and physical properties but neither of then showed a successful commercial exoskeleton with PAMs.

This motivates us to make an exoskeleton suit totally based on PAMs
Which will be light weight, flexible and affordable for all the people having
Upper limb paralysis or amputation and for workers doing over head work

Objective

(a)to study the Human-pneumatic system interaction in much more detail ,

(b)to make the model very light , flexible but yet strong,

(c)to optimize the cost so as to make it affordable to public.

Muscle Fabrication and Testing

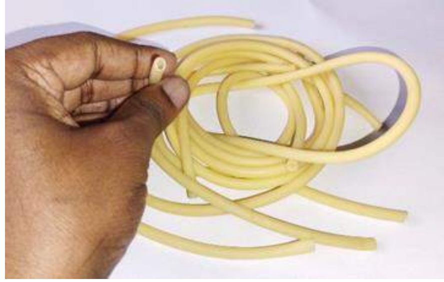
- Our team crafted McKibben-style Pneumatic Artificial Muscles (PAMs) to emulate the behavior of biological muscles.
- These PAMs feature an elastic sleeve (latex or silicone) and parallel reinforcing fibers (fishing line or Kevlar). When pressurized, the fibers contract, inducing radial expansion and axial contraction for a natural linear motion.
- Benefits include a simple design that effectively mimics biological muscle movement, making it ideal for biomechanics applications, especially in replicating human limb movements.

The above three muscles were made of length 22.5, 14, 9 cm respectively.

Fabrication

Material used for making muscles:

- Latex Tubes
- Nylon Sleeves
- Pneumatic pipes
- Clamp Hose
- Zip Ties



Making

- Cut a length of flexible latex tubing with outer and inner diameters of 5mm and 3mm.
- Insert a pneumatic tube into one end of the latex tube, ensuring a slightly larger diameter for a leak-proof seal.
- Wrap the latex tube with a 12mm braided nylon sleeve with a 150% expansion ratio.
- Secure the ends of the sleeve-covered tube with ties and tighten using a hose clamp.
- Attach one end of the tubing to a pneumatic control valve or an air source, like a compressor or hand pump.

Methodology

- The experiment was conducted using a Pneumatic Muscle Testing Apparatus. Due to technological limitations, the pressure values at which the muscles were tested are **205kPa and 220kPa**. Consequently, we conducted the experiment under constant pressure with varying loads.
- We initiated the experiment from a no-load condition and applied weights of **200g, 500g, 700g, and 1kg**.
- Measurements of contractions were recorded for all 3 muscles at each load, including the initial no-load condition.
- For the smallest muscle, the displacement was negligible at 1 kg so we discarded that reading.

Observation Tables

Table 1: Observation Table for 22.5 cm muscle (Contraction in mm)

Load (g) / Pressure (kPa)	0	200	500	700	1000
205	39	36	31	27	22
220	42	38	34	29	24

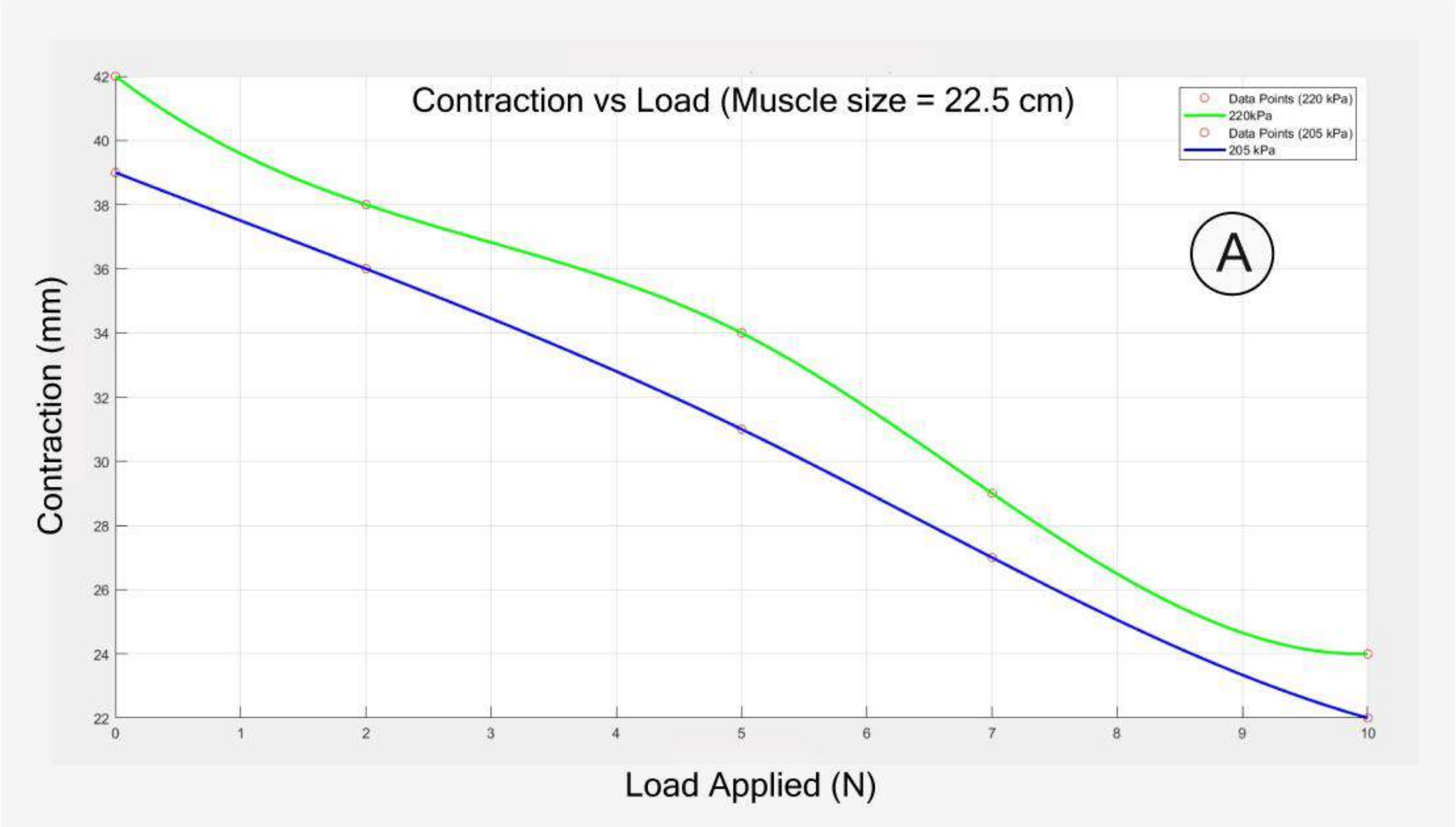
Table 2: Observation Table for 14 cm muscle (Contraction in mm)

Load (g) / Pressure (kPa)	0	200	500	700	1000
205	11	10	7	5	3
220	14	12	10	7	4

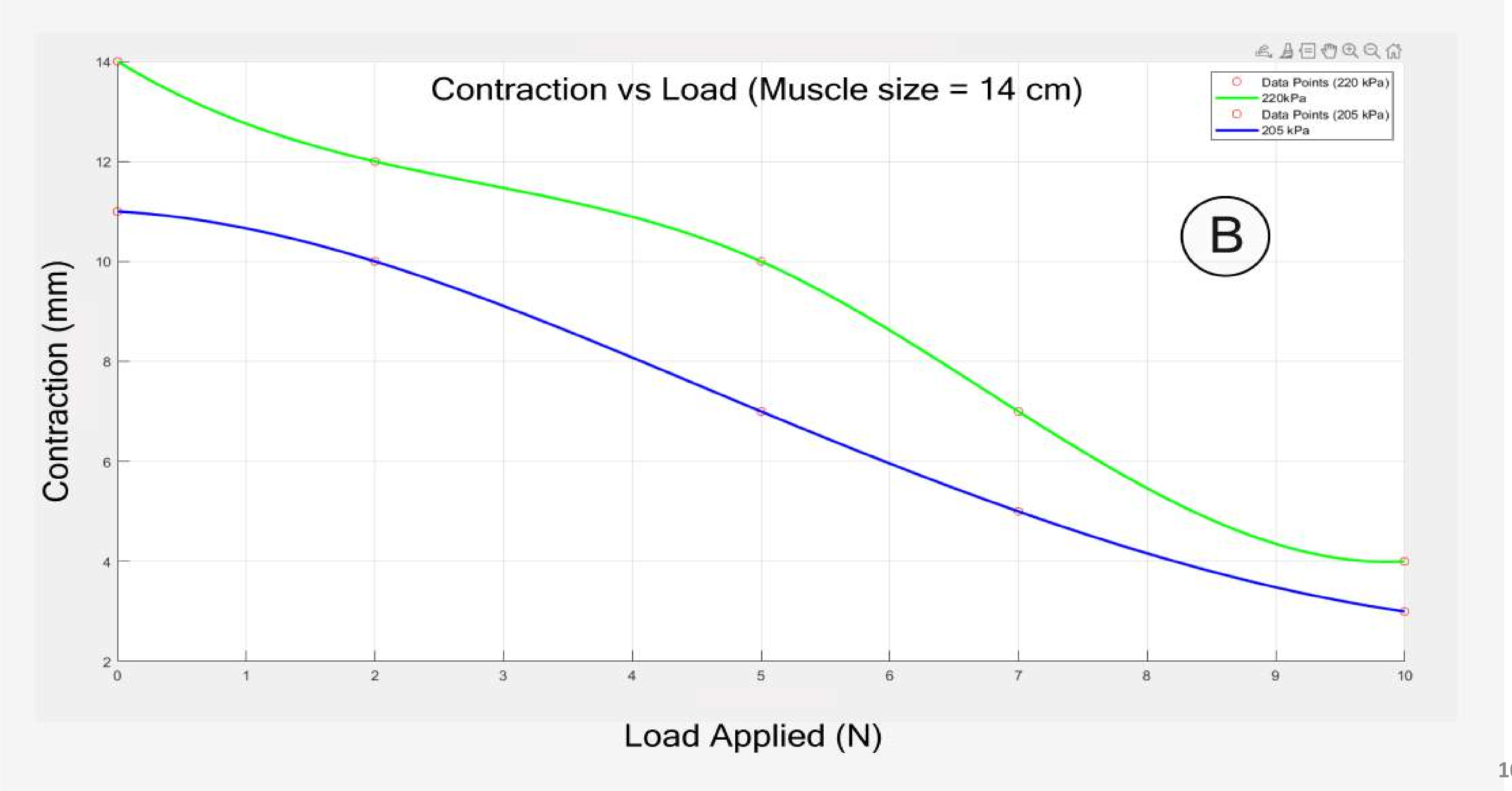
Table 3: Observation Table for 9 cm muscle (Contraction in mm)

Load (g) / Pressure (kPa)	0	200	500	700
205	8	5	3	2
220	9	7	6	4

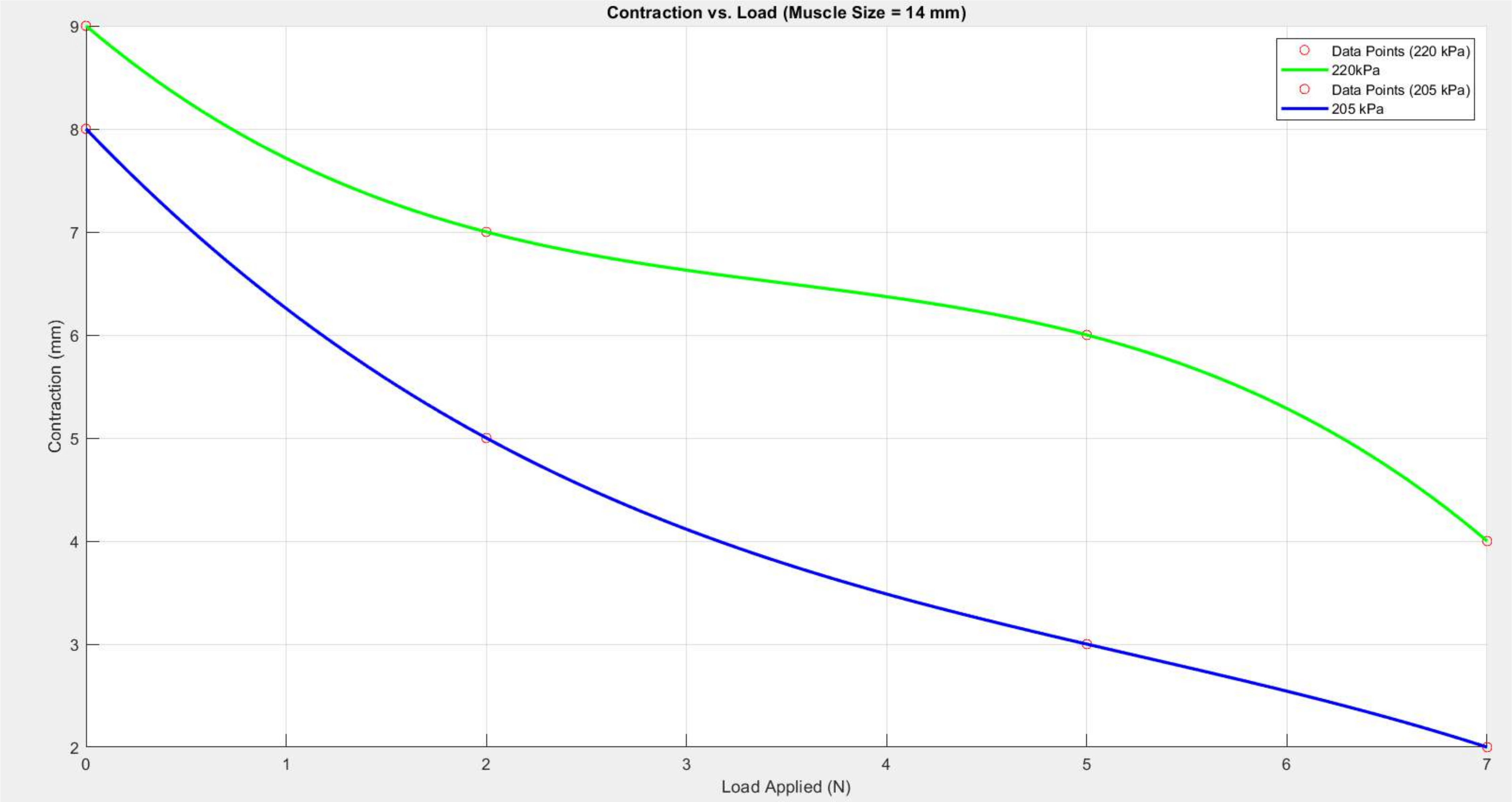
Results : For 22.5 cm muscle



Results : For 14 cm muscle



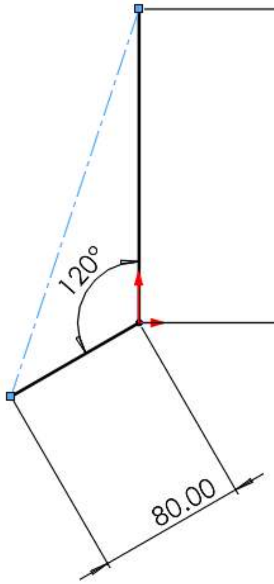
Results : For 9 cm muscle



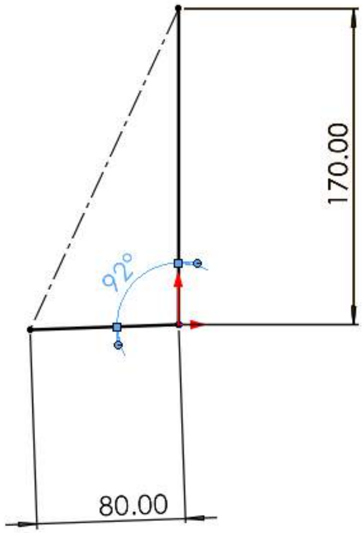
Implementation of PAM : Elbow Joint

1. **Experimental Setup:** A specially designed pneumatic artificial muscle, affixed to a wooden dummy arm, mimicked human arm biomechanics in a revolute elbow joint. Nails were strategically placed at 17 cm and 8 cm from the elbow in the upper and forearm segments.
2. **Muscle Characteristics:** Pressurized at 30 psi, the 22.5 cm pneumatic muscle exhibited a substantial 16.5% contraction, measuring 18.8 cm. This contraction generated significant torque, rotating the revolute elbow joint by 28 degrees from its initial 120-degree position.

Before



After

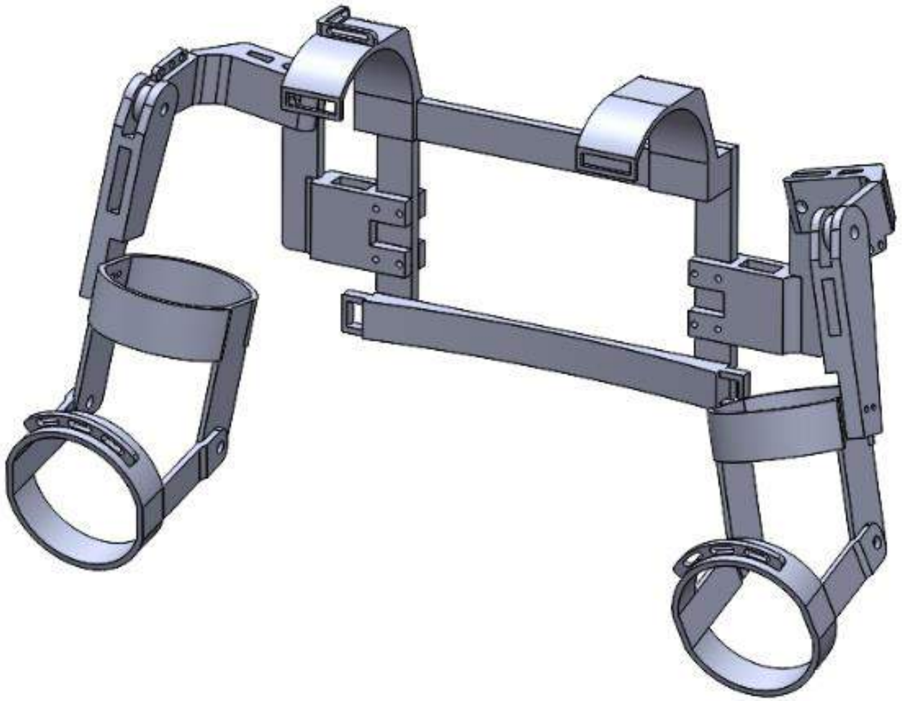


Implementation

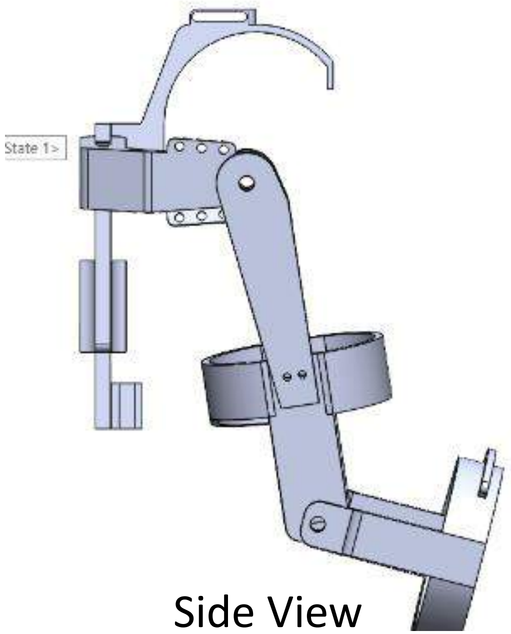
- **Performance Evaluation:** The results emphasize the pneumatic artificial muscle's effectiveness in producing substantial mechanical output. The recorded contraction and torque highlight its potential for replicating human-like joint movements in biomechanical applications.

Design of Exoskeleton

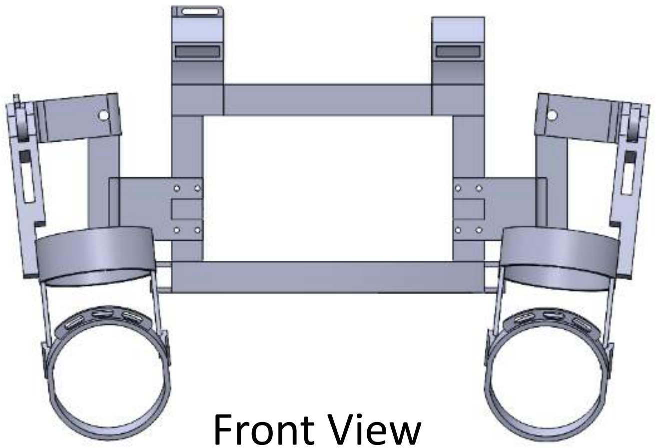
A 3 DoF exoskeleton is developed enabling the user to perform all possible Flexion and Abduction motion without any restraint from the model.



Isometric View



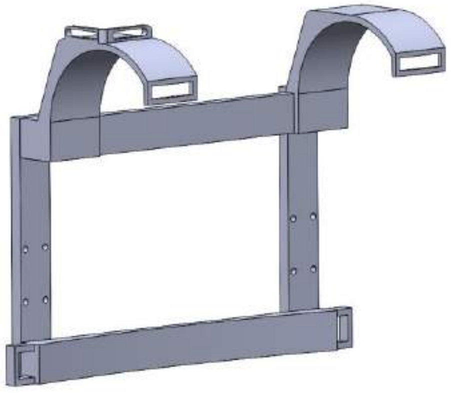
Side View



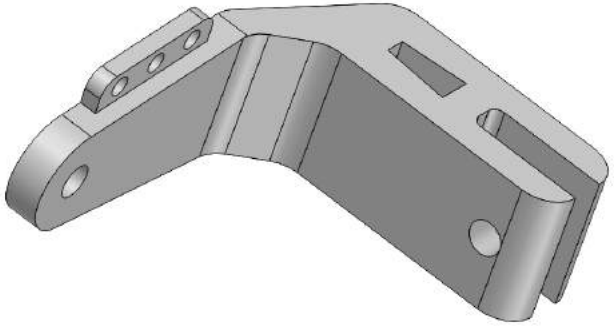
Front View

Components of the Exoskeleton Model

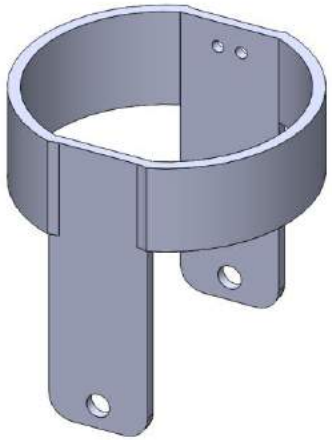
The components are distinctly named and will be used to denote them further in the presentation



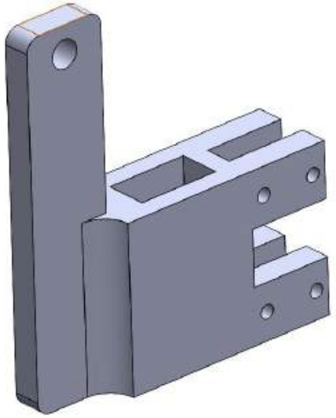
Back Frame



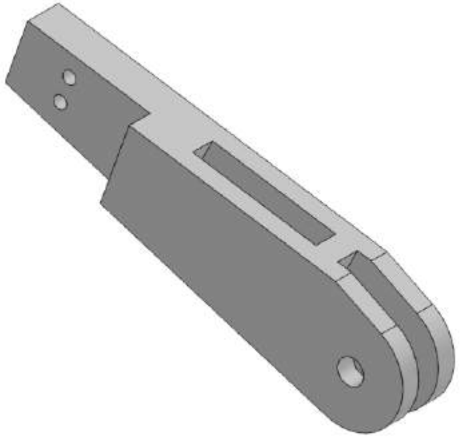
Link 2



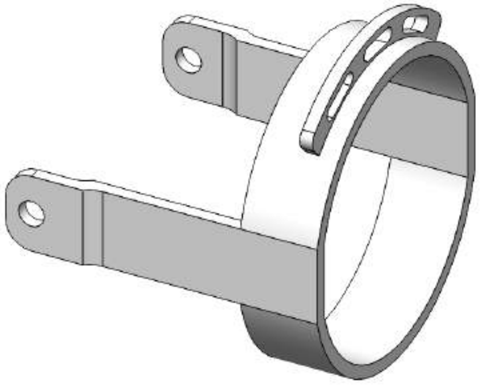
Upper Arm



Link 1



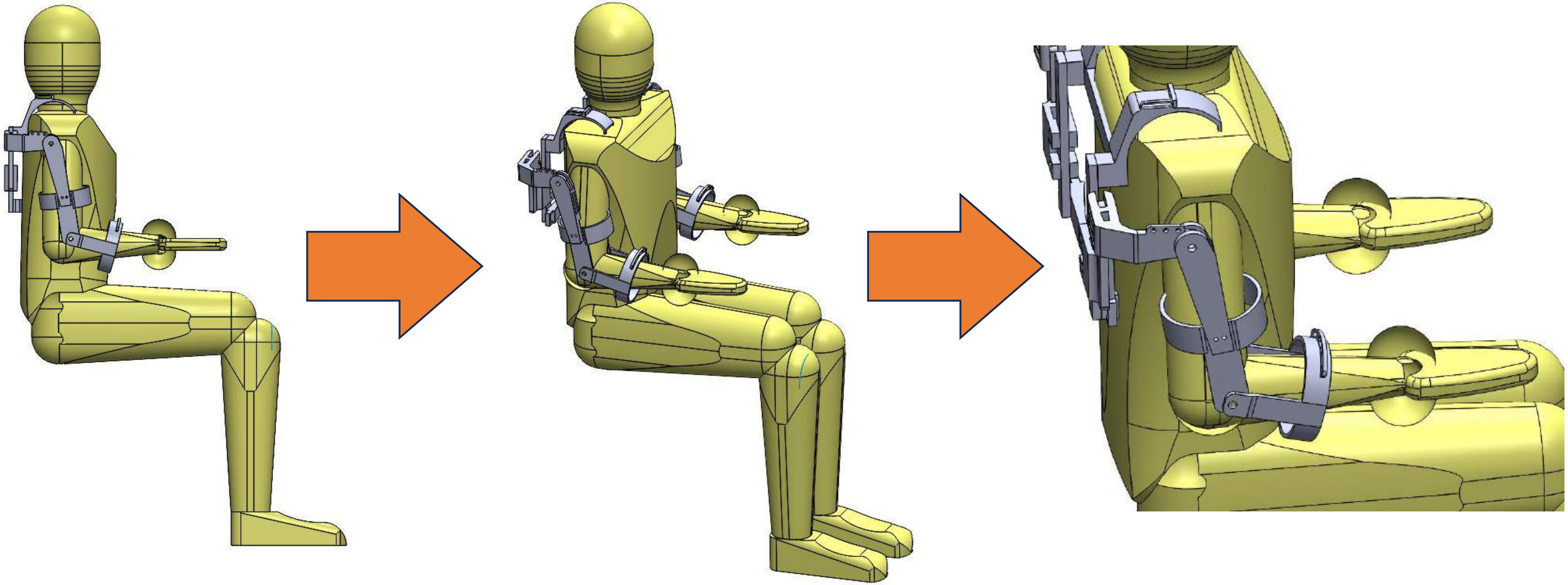
Link 3



Fore arm

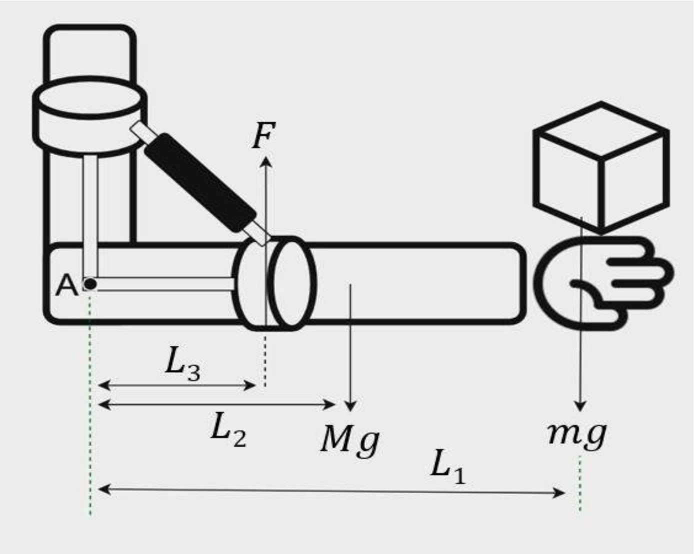
Exoskeleton on a Humanoid Dummy

The exoskeleton placed on a humanoid dummy to check the fittings on Human body



Static Force Analysis

(a) Forearm

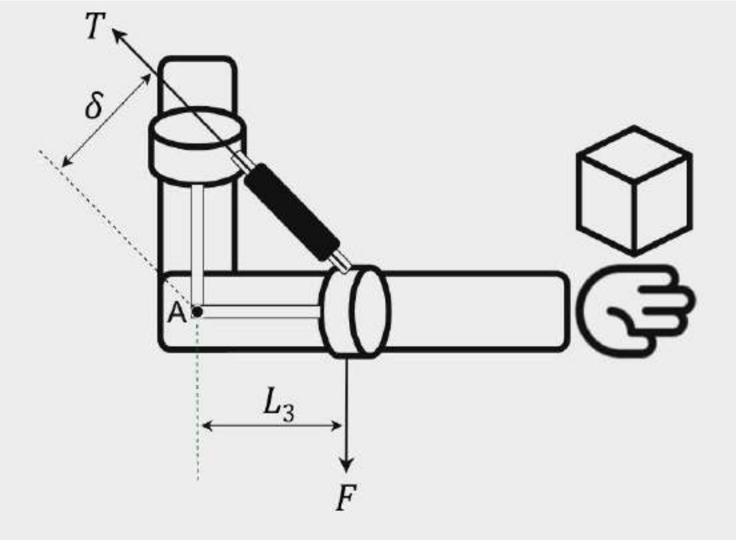


Forces on forearm

Torque balance about point A,

$$.F \times L_3 = Mg \times L_2 + mg \times L_1$$

$$F = [ML_2 + mL_1] \times \frac{g}{L_3}$$



Forces on exoskeleton forearm

Torque balance about point A,

$$T \times \delta = F \times L_3$$

$$T = F \times \frac{L_3}{\delta}$$

Static Force Analysis

(a) Forearm

M = 1.84 kg L_2 = 120 mm g = 9.81 $\mathrm{N \cdot kg \cdot m/s^2}$

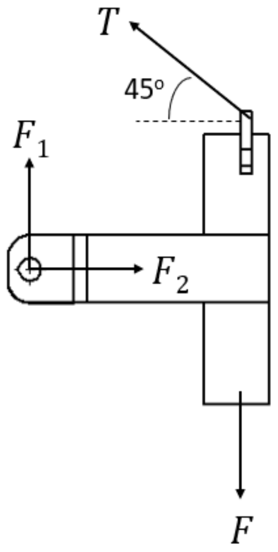
L_1 = 290 mm L_3 = 100 mm

m (kg)	F (N)	T (N)
0	21.638	18.269
1	50.058	42.265
2	78.478	69.089
4	135.318	114.250
5	163.738	138.239

Calculation of forces for different values of m

Static Force Analysis

(a) Forearm



Forces on Forearm link

$$F_1 = F - T\, sin\, 45°$$

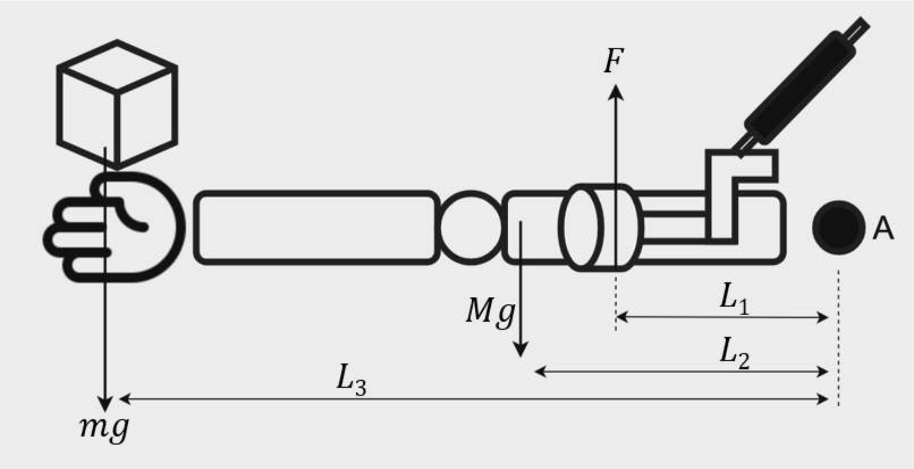
$$F_2 = T \cos 45°$$

m (kg)	F_1 (N)	F_2 (N)
0	8.720	12.918
1	20.172	29.886
2	29.625	48.853
4	54.531	80.787
5	65.988	97.750

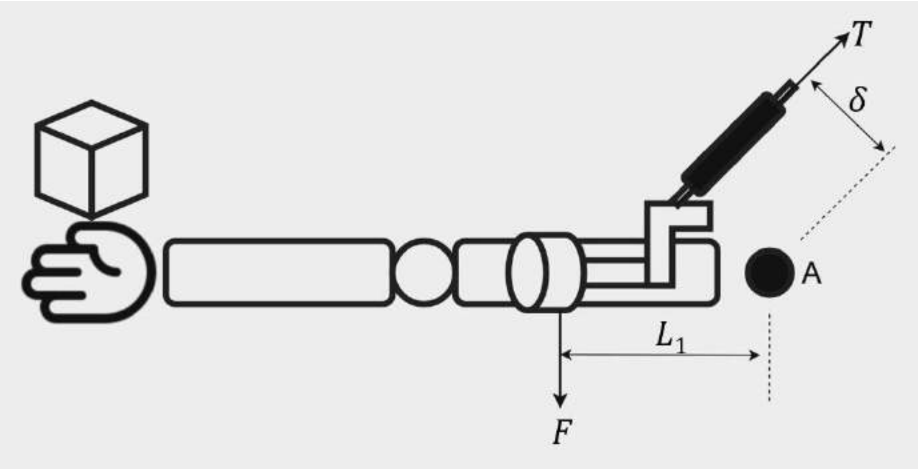
Calculation of forces for different values of m

Static Force Analysis

(b) Shoulder



Forces on upper limb at abduction



Forces on exoskeleton shoulder

Torque balance about point A,

$$F \times L_1 = Mg \times L_2 + mg \times L_3$$

$$F = [ML_2 + mL_3] \times \frac{g}{L_1}$$

Torque balance about point A,

$$T \times \delta = F \times L_1$$

$$T = F \times \frac{L_1}{\delta}$$

Static Force Analysis

(a) Lower Arm

M = 4.8 kg L_2 = 240 mm δ = 150 mm

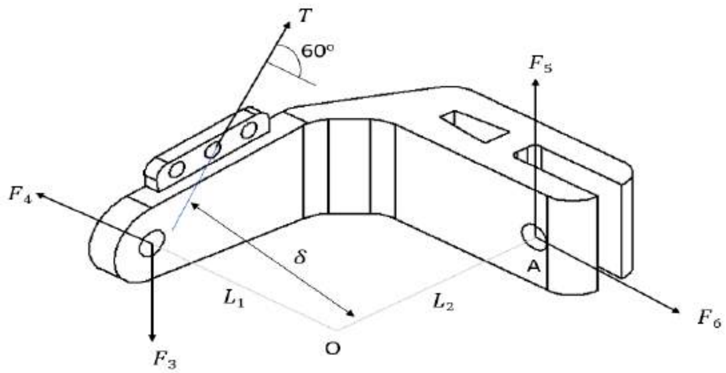
L_1 = 155 mm L_3 = 550 mm $g = 9.81\ \mathrm{N \cdot kg \cdot m/s^2}$

m (kg)	F (N)	T (N)
0	72.834	75.264
1	107.611	111.197
2	142.383	147.131
4	177.159	183.064
5	211.926	218.990

Calculation of forces for different values of m

Static Force Analysis

(a) Lower Arm



Forces on Link 2

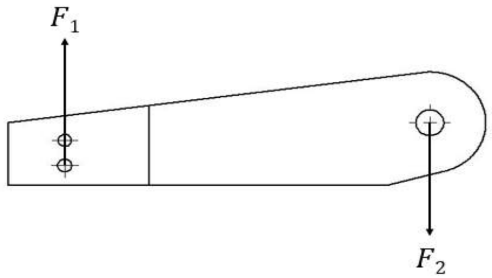
$$F_1 = F_2 = F$$

$$F_4 = 0$$

$$F_3 = F$$

$$F_5 = T \sin 60° - F_3$$

$$F_6 = -T \cos 60°$$



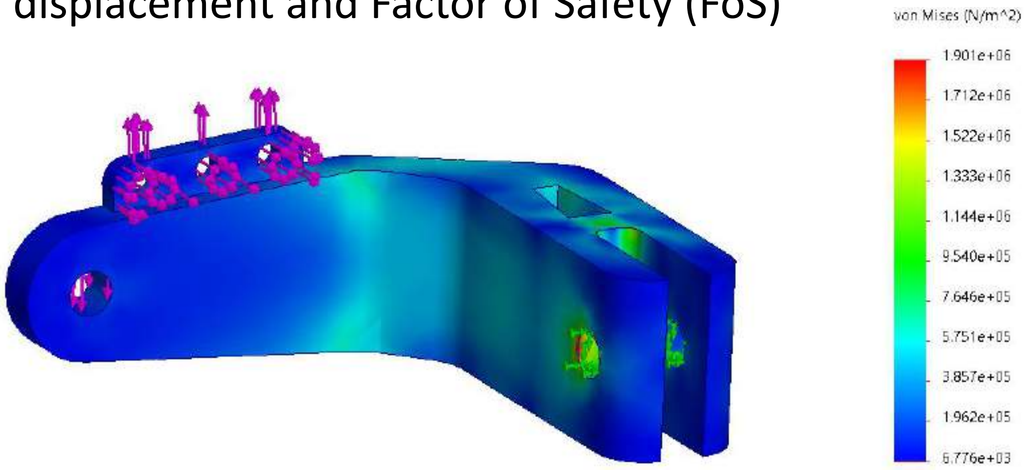
Forces on Link 3

m (kg)	T (N)	F_3 (N)	F_5 (N)	F_6 (N)
0	75.264	75.264	-10.0835	-37.632
1	107.611	111.197	-18.0031	-53.8055
2	142.383	147.131	-23.8237	-71.1915
4	177.159	183.064	-29.6398	-88.5795
5	211.926	218.989	-35.4557	-105.963

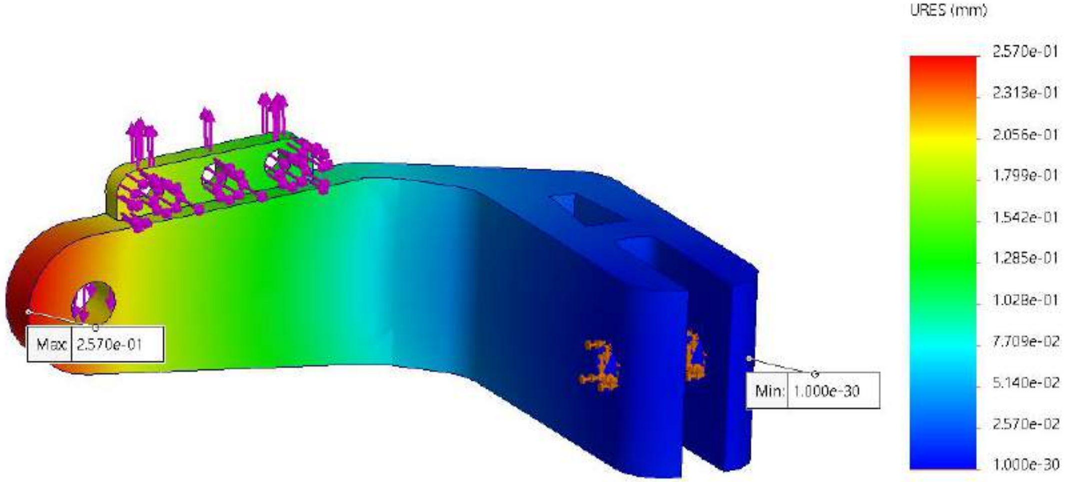
Calculation of forces for different values of m

Static Force Simulation on Critical Components

Based on the static force calculations, FEM simulations were performed on 3 most critical components of the exoskeleton namely: Link 2, Link 3, and Forearm. The main point of focus were the values and location of stresses, displacement and Factor of Safety (FoS)



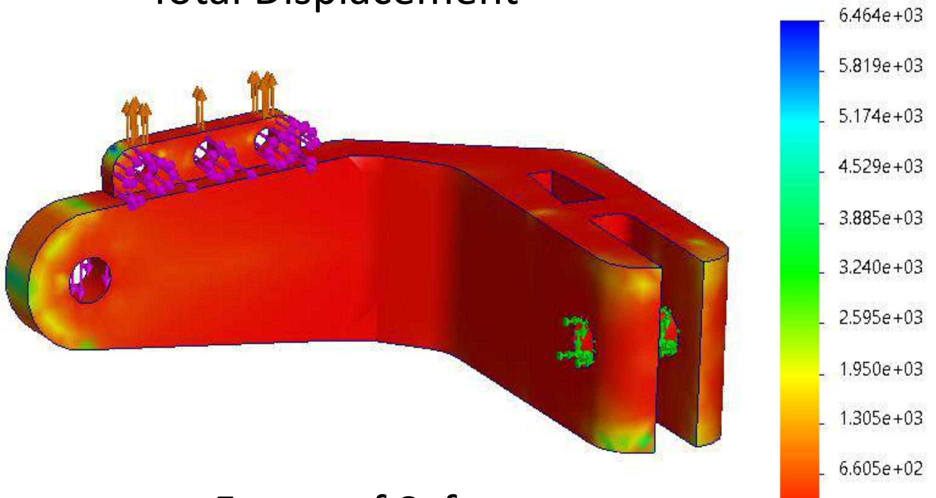
Von Mises Stress



Total Displacement

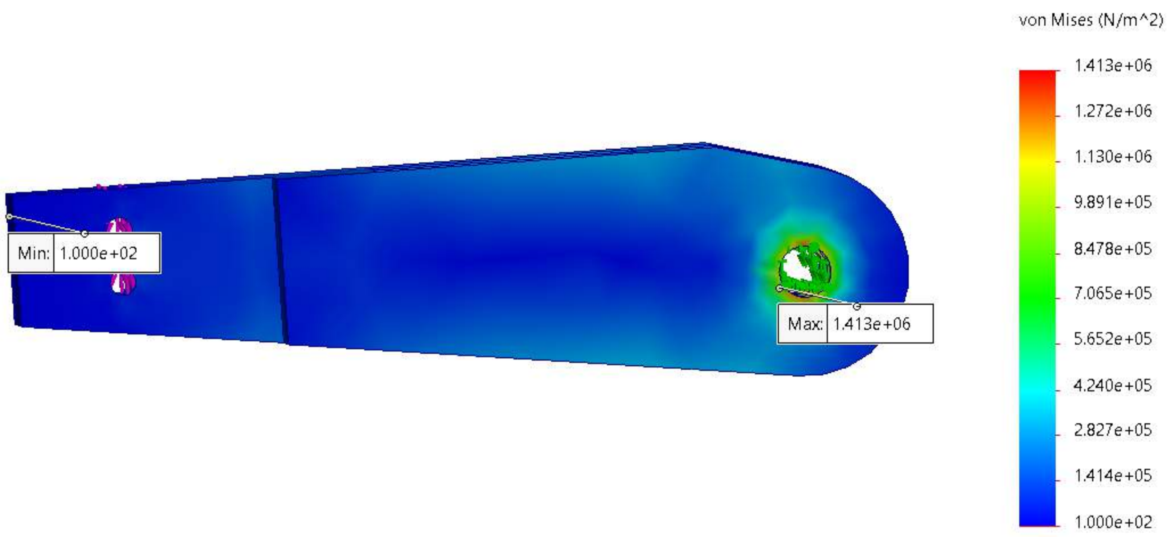
Max Stress = $1.9e^{+06}$ N/m^2

Max Disp. = 0.257 mm

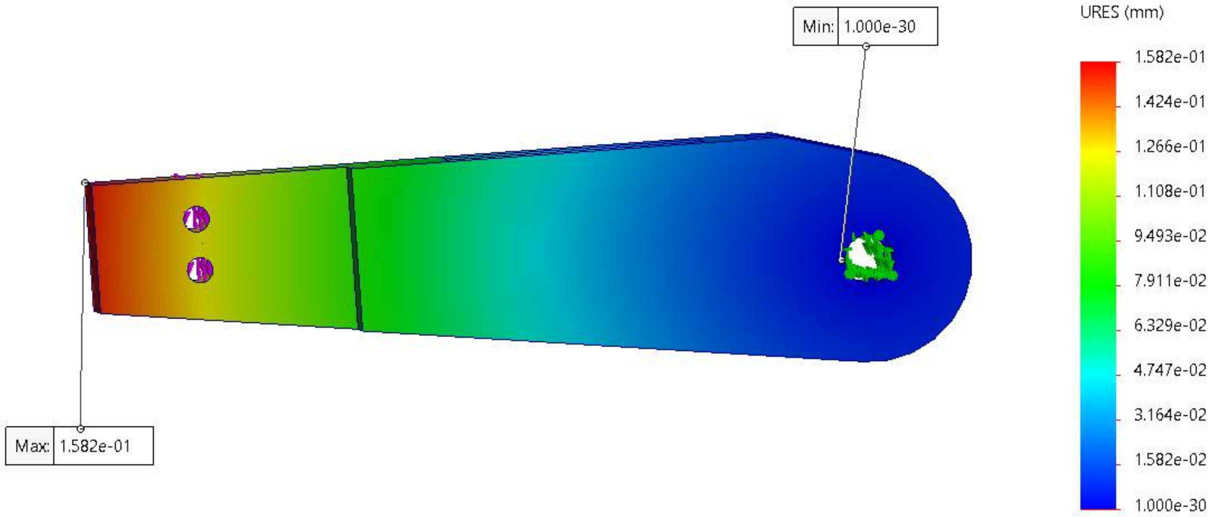


Factor of Safety

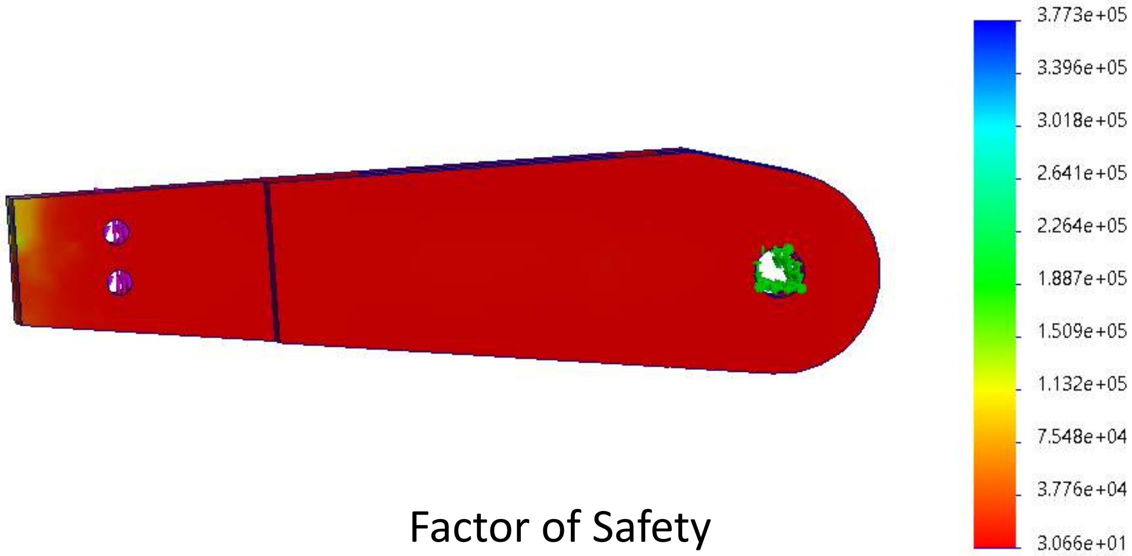
Static Force Simulation on Critical Components



Von Mises Stress

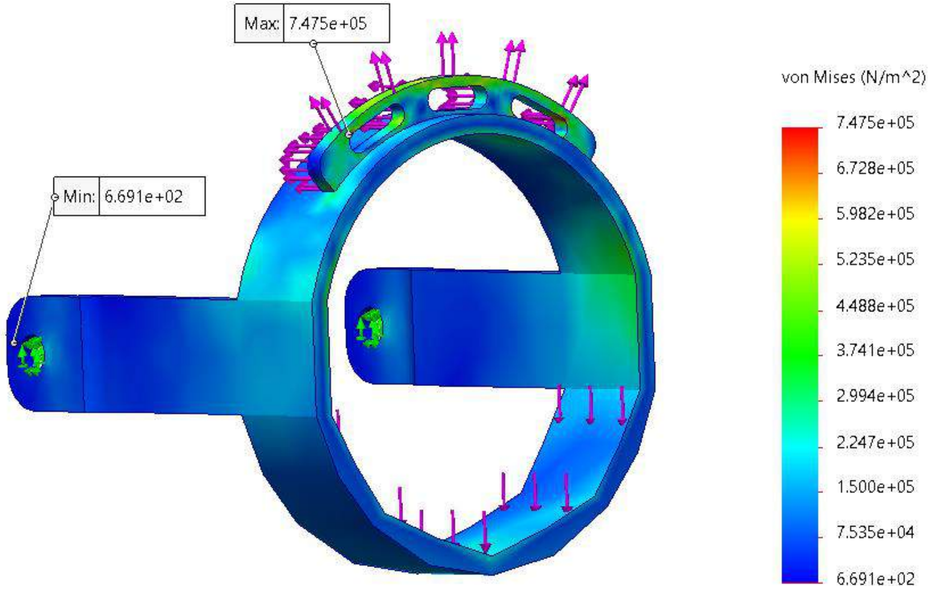


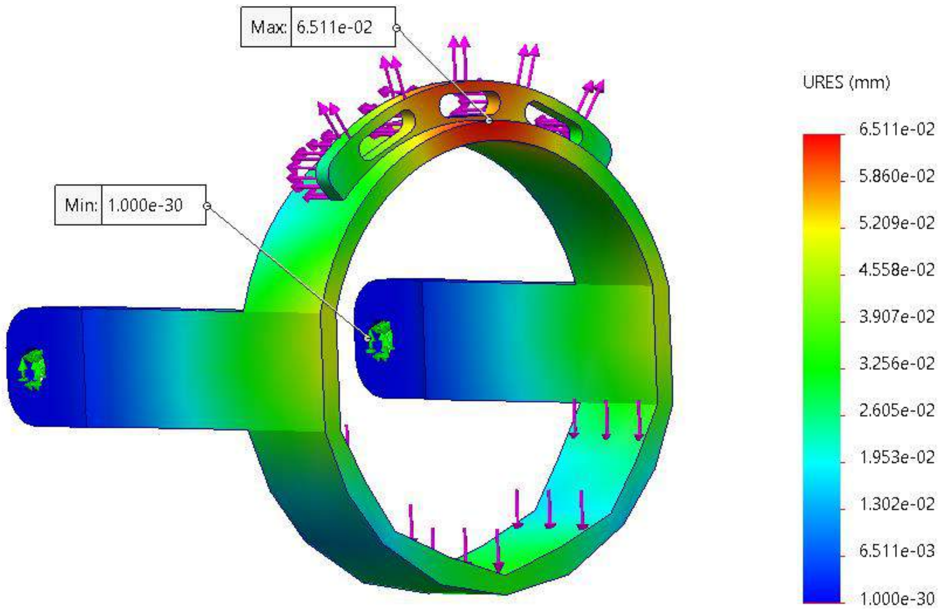
Total Displacement



Factor of Safety

Static Force Simulation on Critical Components

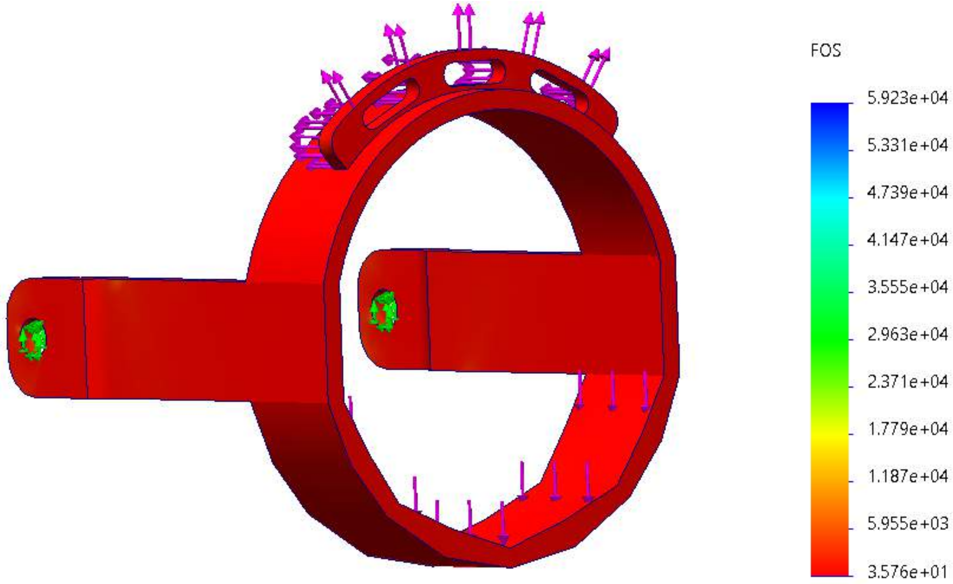




Max Stress =

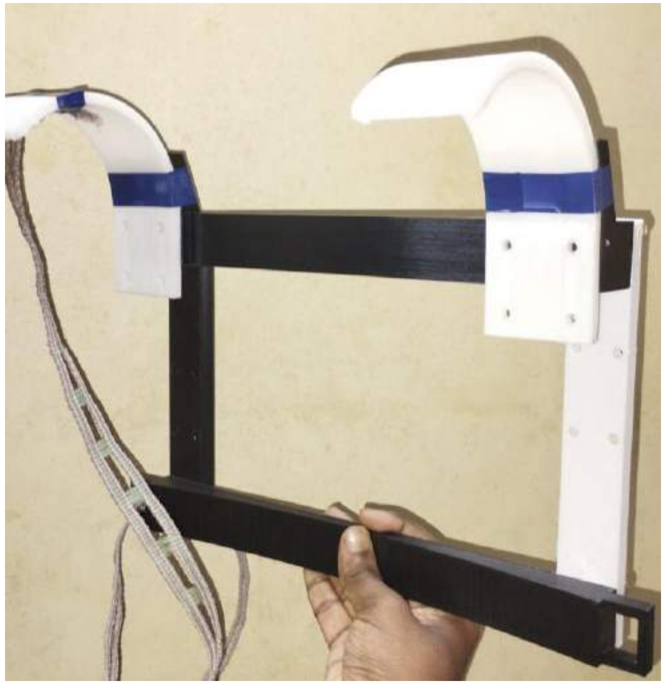
Max. Displacement =

Factor of Safety =

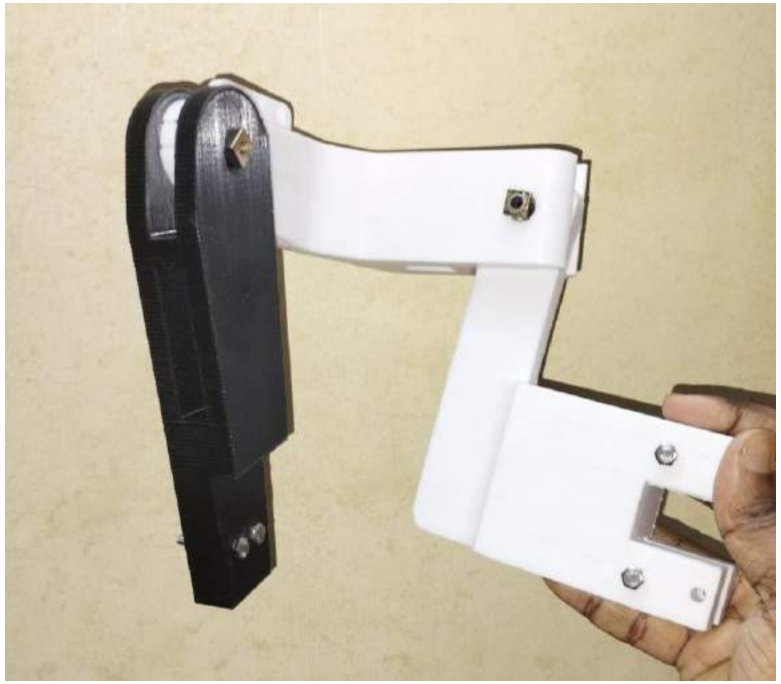


Physical Model of Exoskeleton

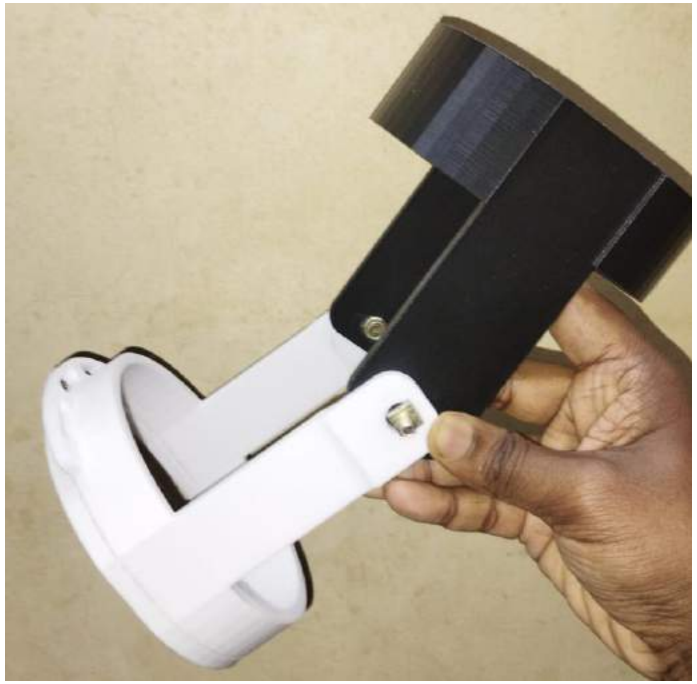
Based on the CAD model, a 3D printed physical model was manufactured using PLA to carry out the experiments on real human arms. The model primarily consists of three major parts, the Back Frame, the Shoulder Join, and the Elbow Joint



Back Frame

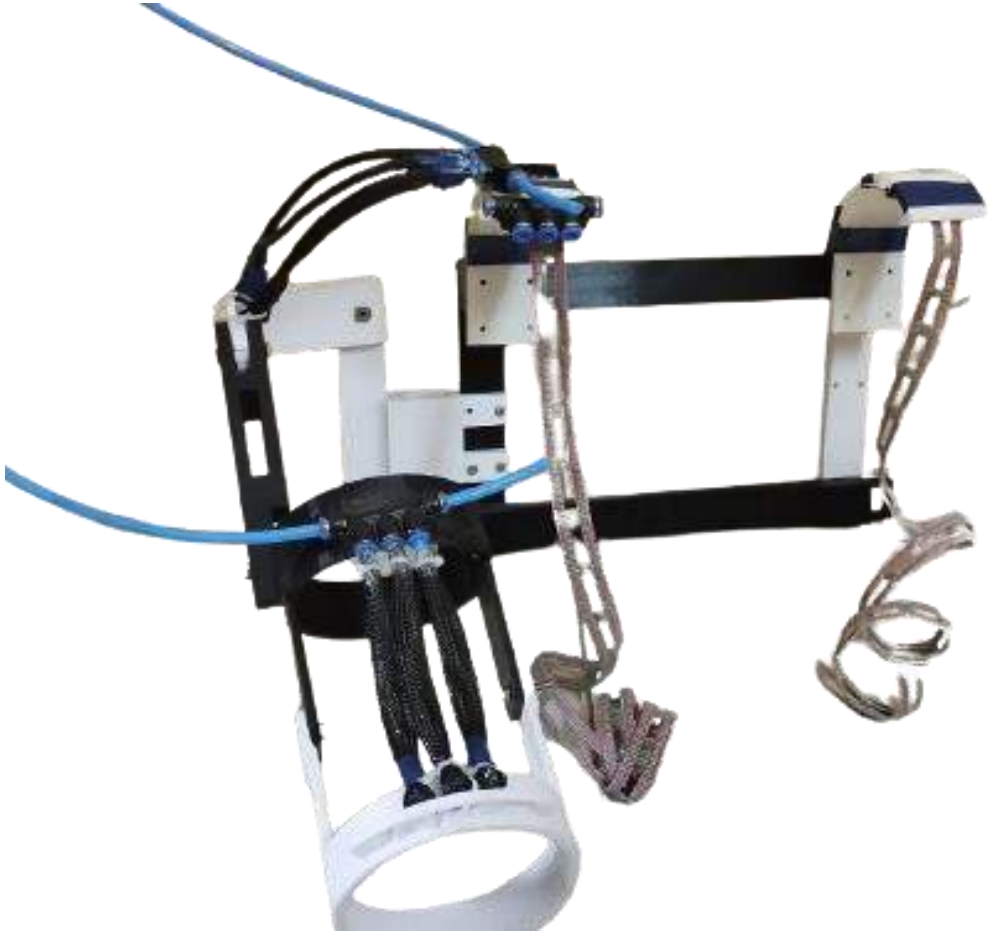


Shoulder Joint

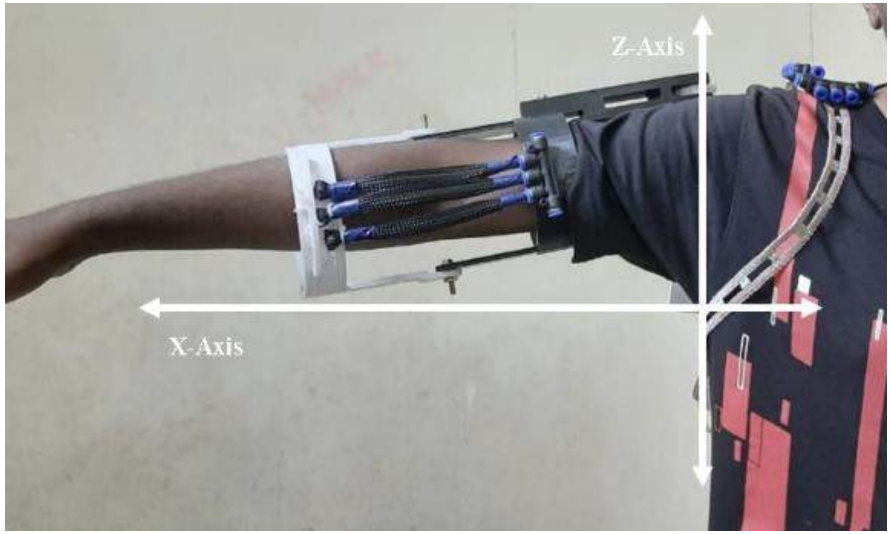


Elbow Joint

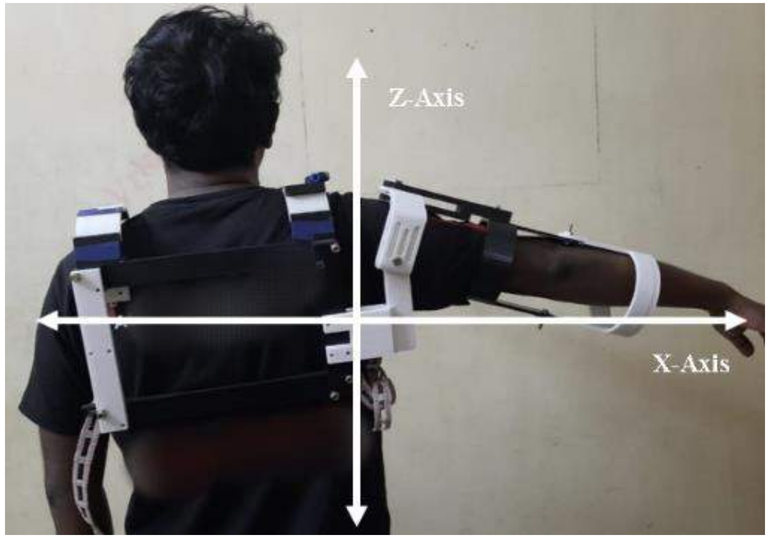
Exoskeleton Assembly



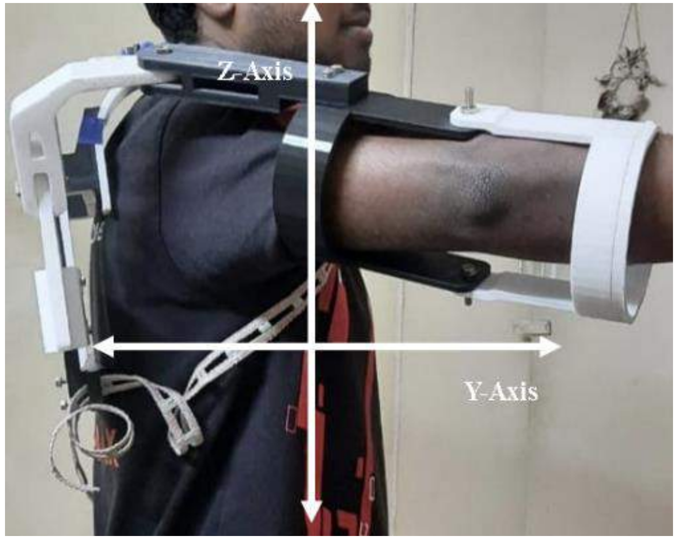
Exoskeleton on Human Arm



Abduction Front View



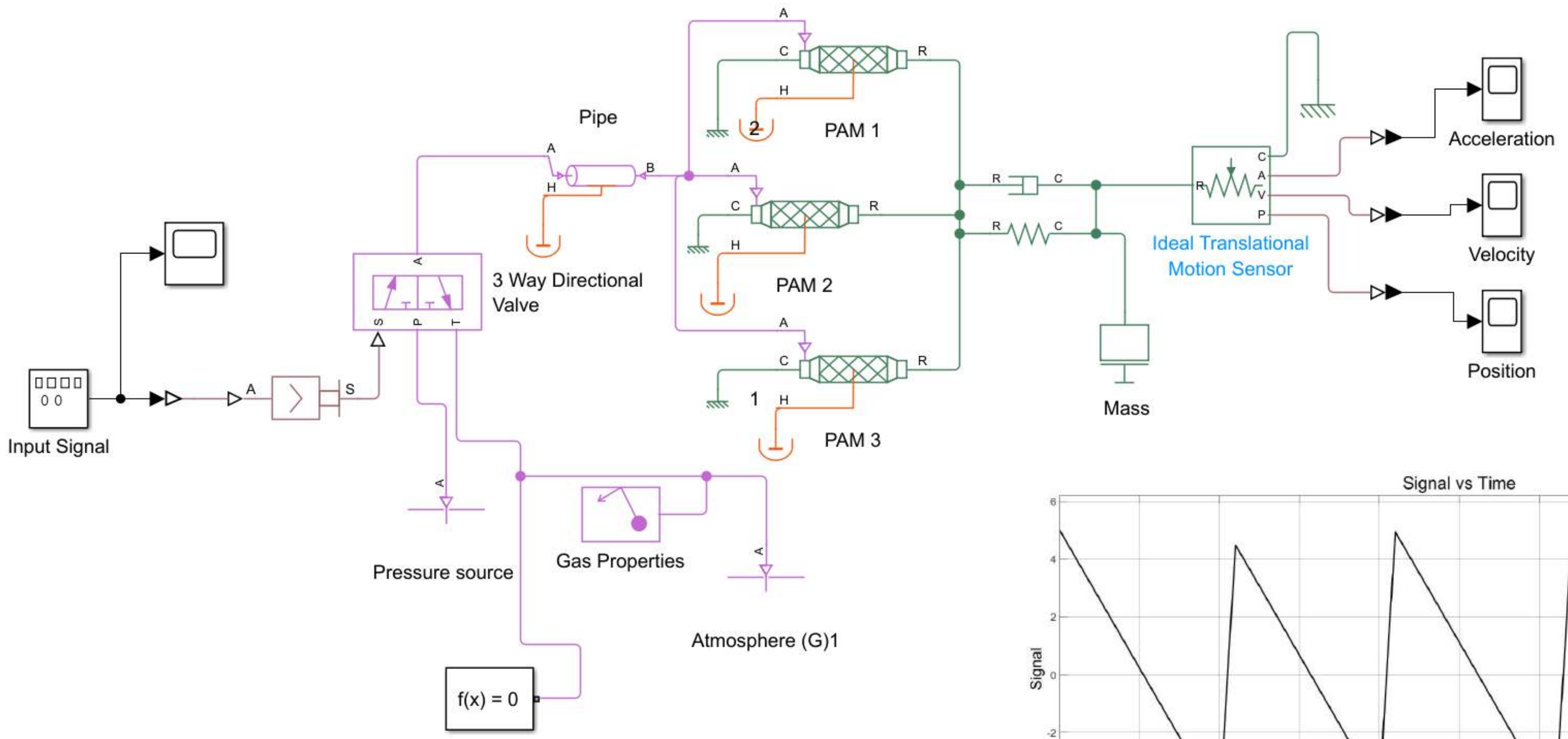
Abduction Back View



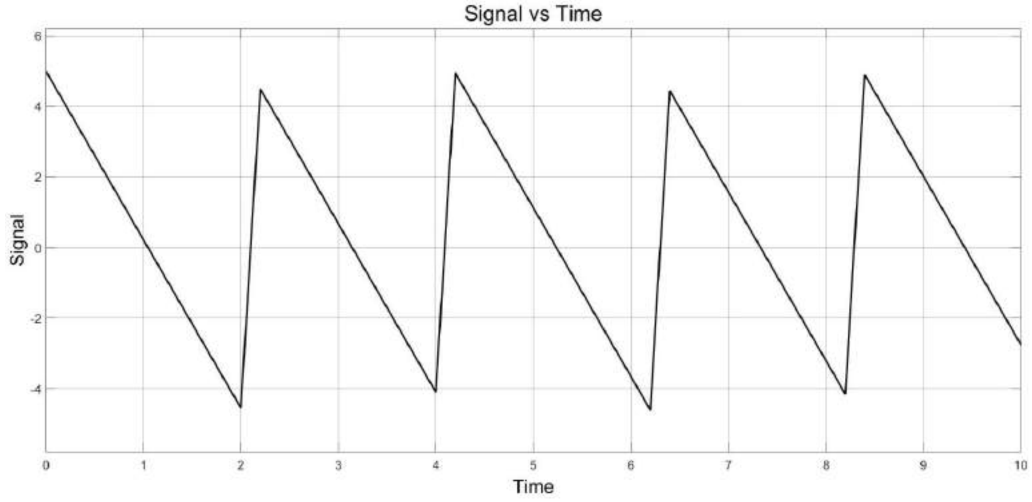
Flexion Side View

Normal Stance

Simulink Model of PAM

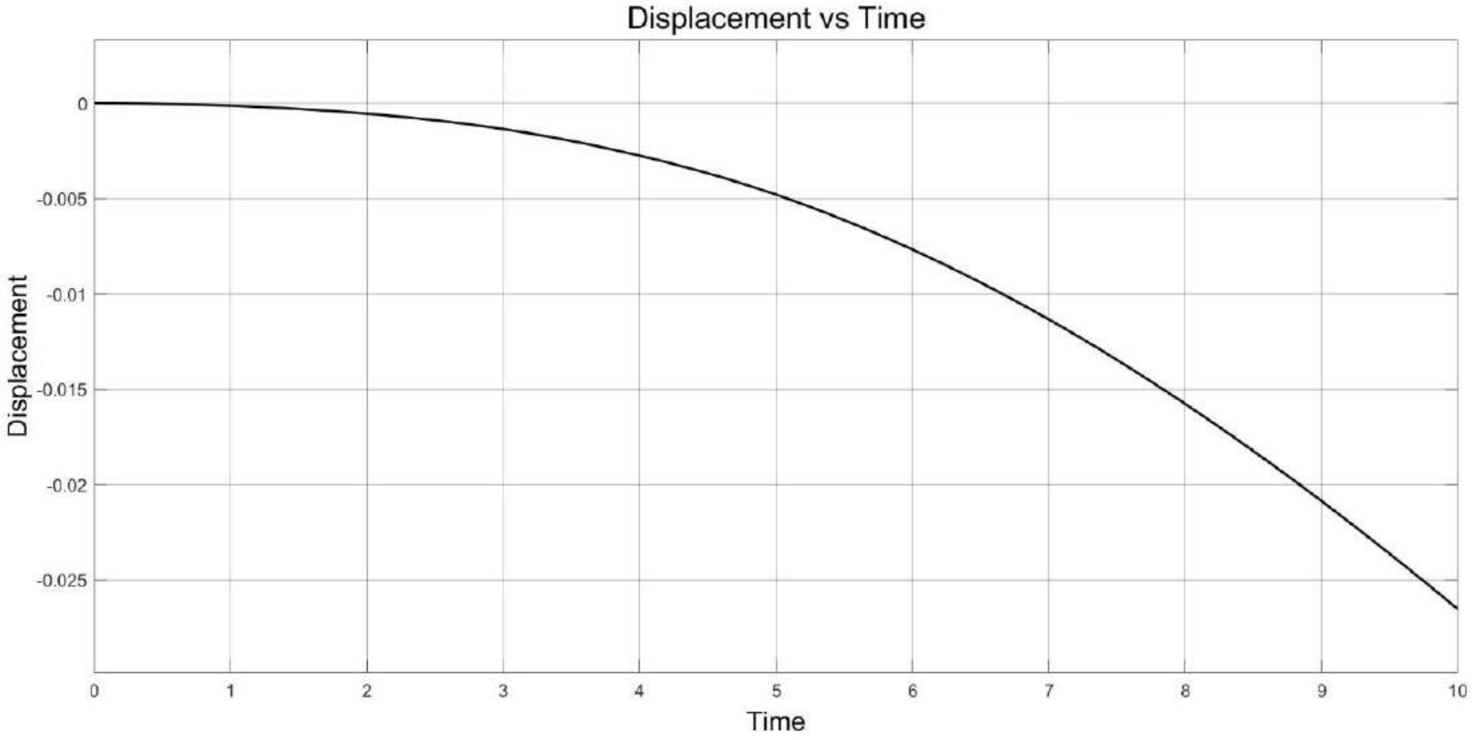


Simulink Model of PAM



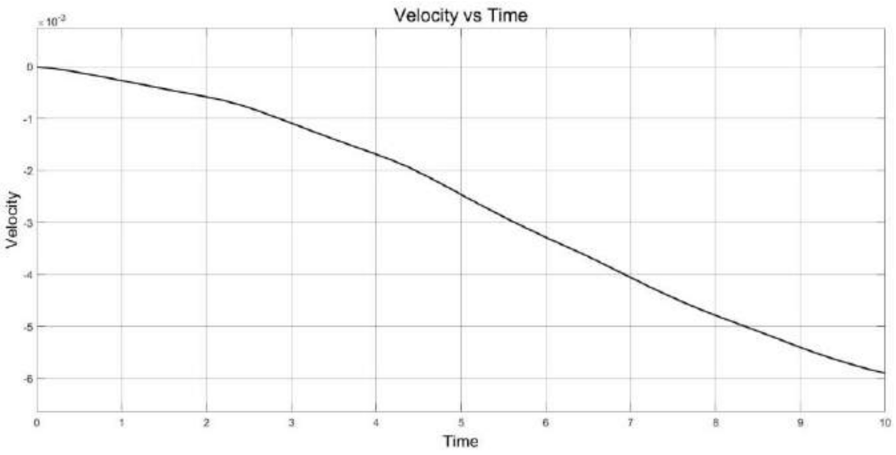
Input Signal (Saw Tooth)

Simulink Model Output

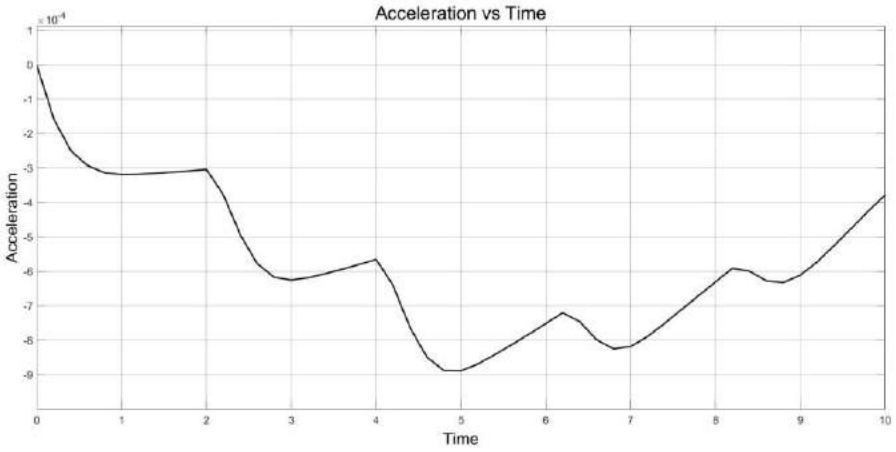


Displacement (Contraction of Muscle)

A contraction of 26.2 mm is obtained from the Simulink model.

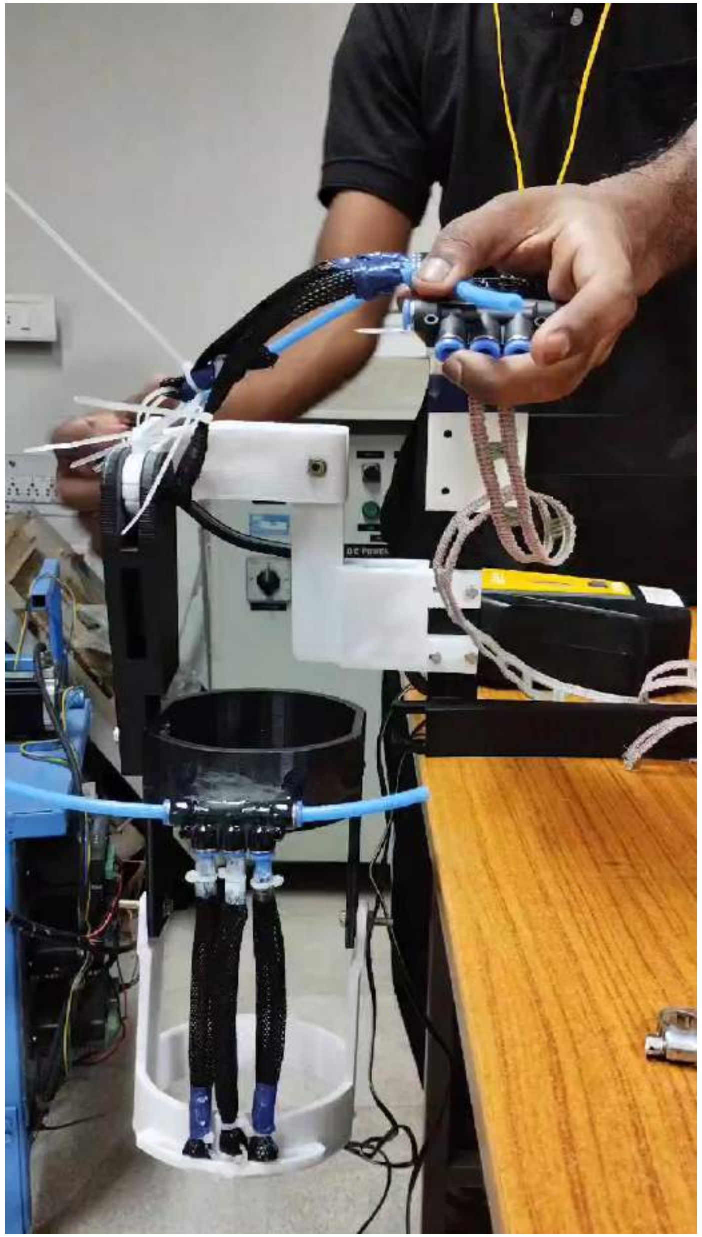


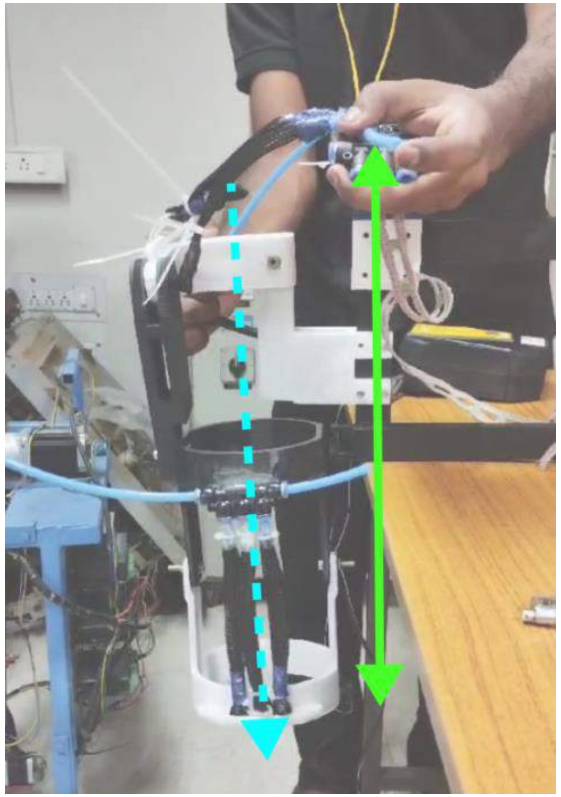
Velocity

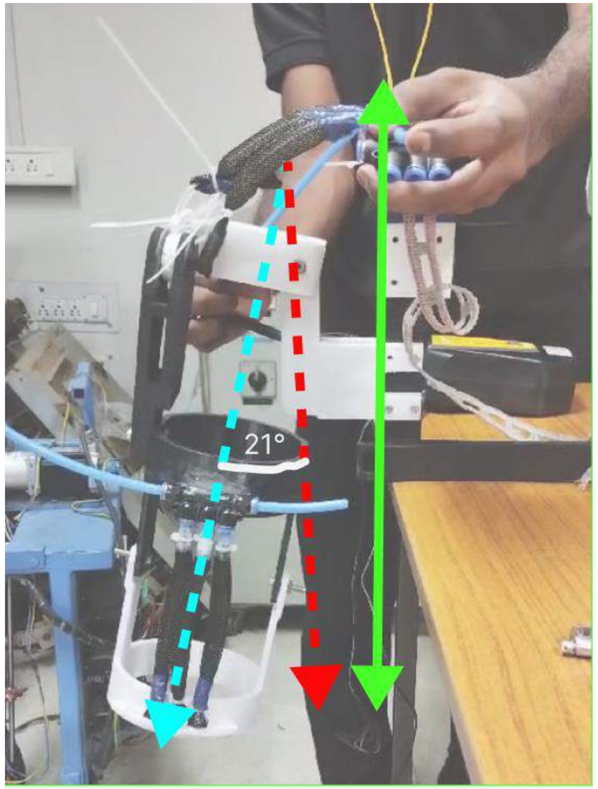


Acceleration

Demonstration of muscle actuation at 3 bar

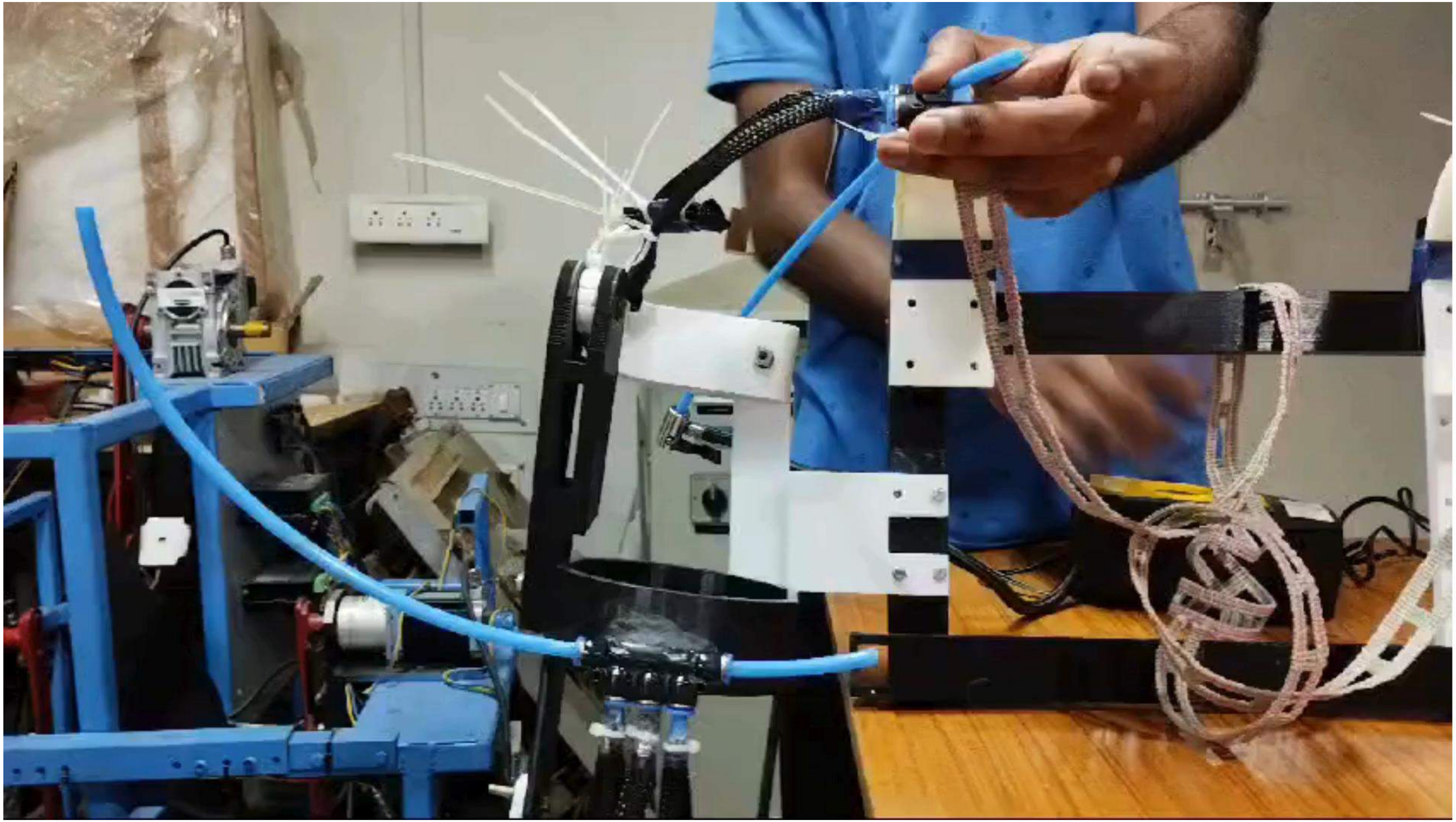




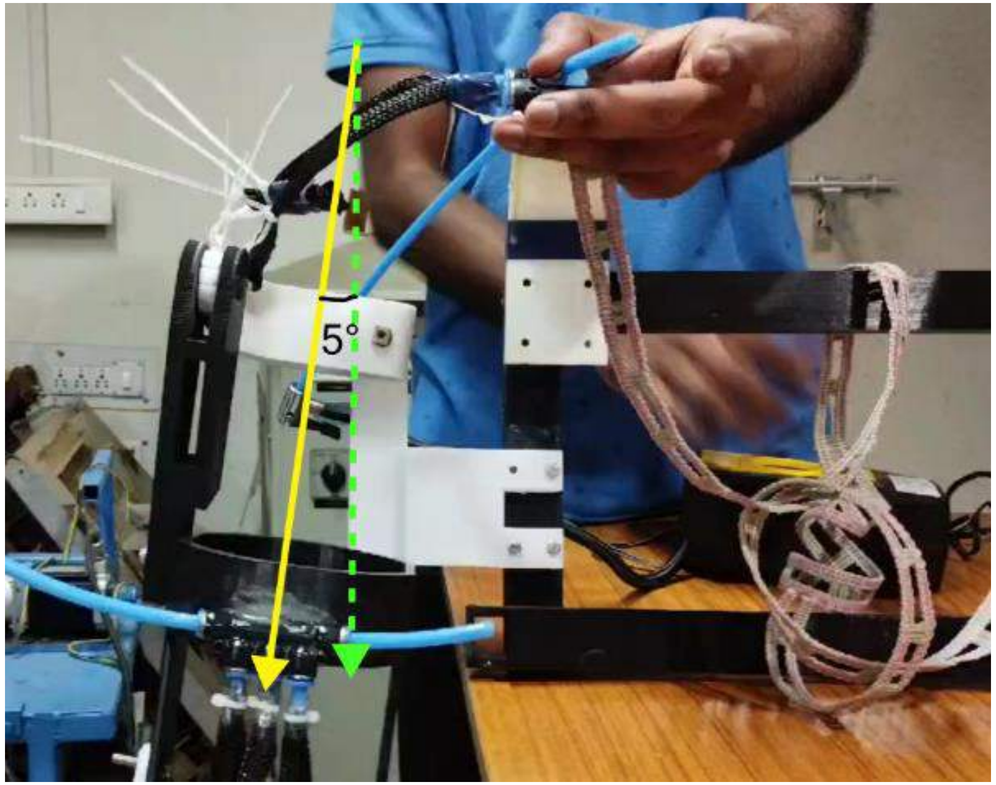


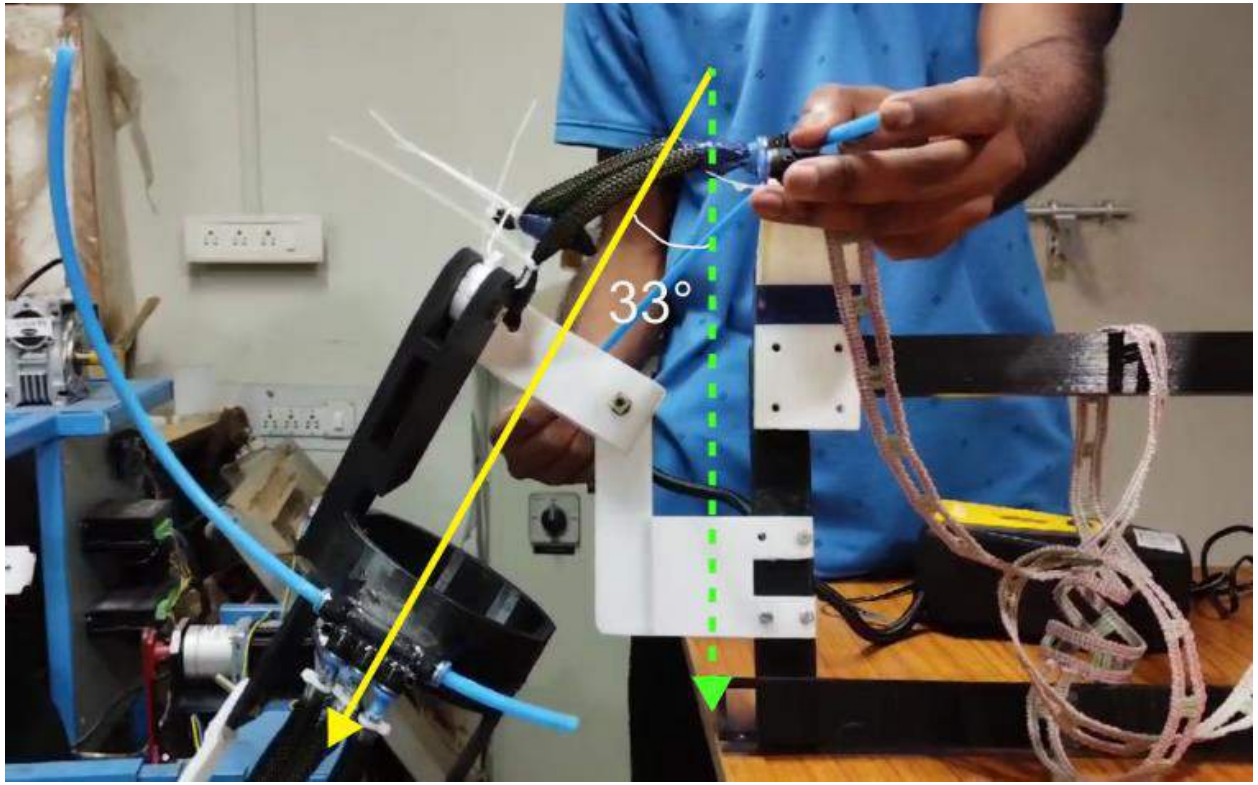
The PAMs were tested at no load condition at the shoulder joint at 3 bar and 5 bar respectively. The corresponding video shows the motion of the exoskeleton at 3 bar pressure

Demonstration of muscle actuation at 5 bar



Demonstration of muscle actuation at 5 bar





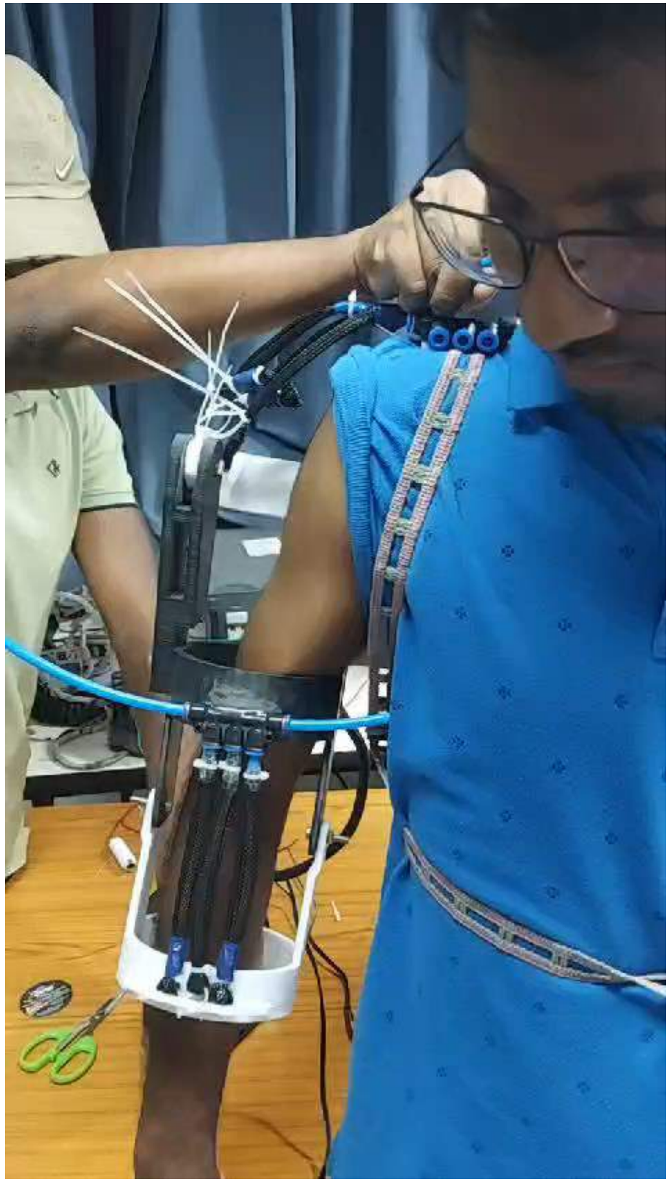
Pressure of 5 bar was applied on the same group of PAMs resulting in a rotation 28° from initial position.

Demonstration on Human Arm

The model was tested on human for experimentation. On pressure of 5 bar, a deflection of 10^{o} was obtained.

Demonstration on Elbow Joint

Challenges faced



Conclusion

❖ From the muscle loading experiment, the following can be concluded:

- Contraction is Directly proportional to the pressure applied.
- Contraction is inversely proportional to load applied.
- Contraction is directly proportional to the length of muscle.
- At higher pressure and longer muscle lengths, the PAMs behave linearly.

❖ A contraction of 16.5% of the initial length of the muscle was achieved while testing it on a wooden dummy of human arm which was able to lift a arm of 800g applying a torque of 640 N-mm was exerted resulting a rotation of 28^{o} at the joint.

❖ A simulation of the PAMs was done on Simulink, where the length of muscles is kept 15 cm and a mass of 4 kg as a load. From the simulation results, the displacement of 26.2 mm was obtained.

Scope for Future Work

- This semester (8th semester), we focused on designing an exoskeleton on which PAMs can be implemented. We started with the CAD and then performed structural analysis. We manufactured the physical model and attached PAMs to the joints and performed the actuation and tested on human arms.

- The scope for future work can be:

➢ Designing a automatic pneumatic control system which can be used to actuate the muscles using remote control or voice control consisting of all the different types of valve. .

➢ improve the exoskeleton model to make it more efficient.

➢ Involving cables to the exoskeleton to distantly control with the PAMs.

➢ Test the model on a human upper limbs.

THANK YOU!