3D-Printed 4-Bar Linkage Prosthetic Knee

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Abstract

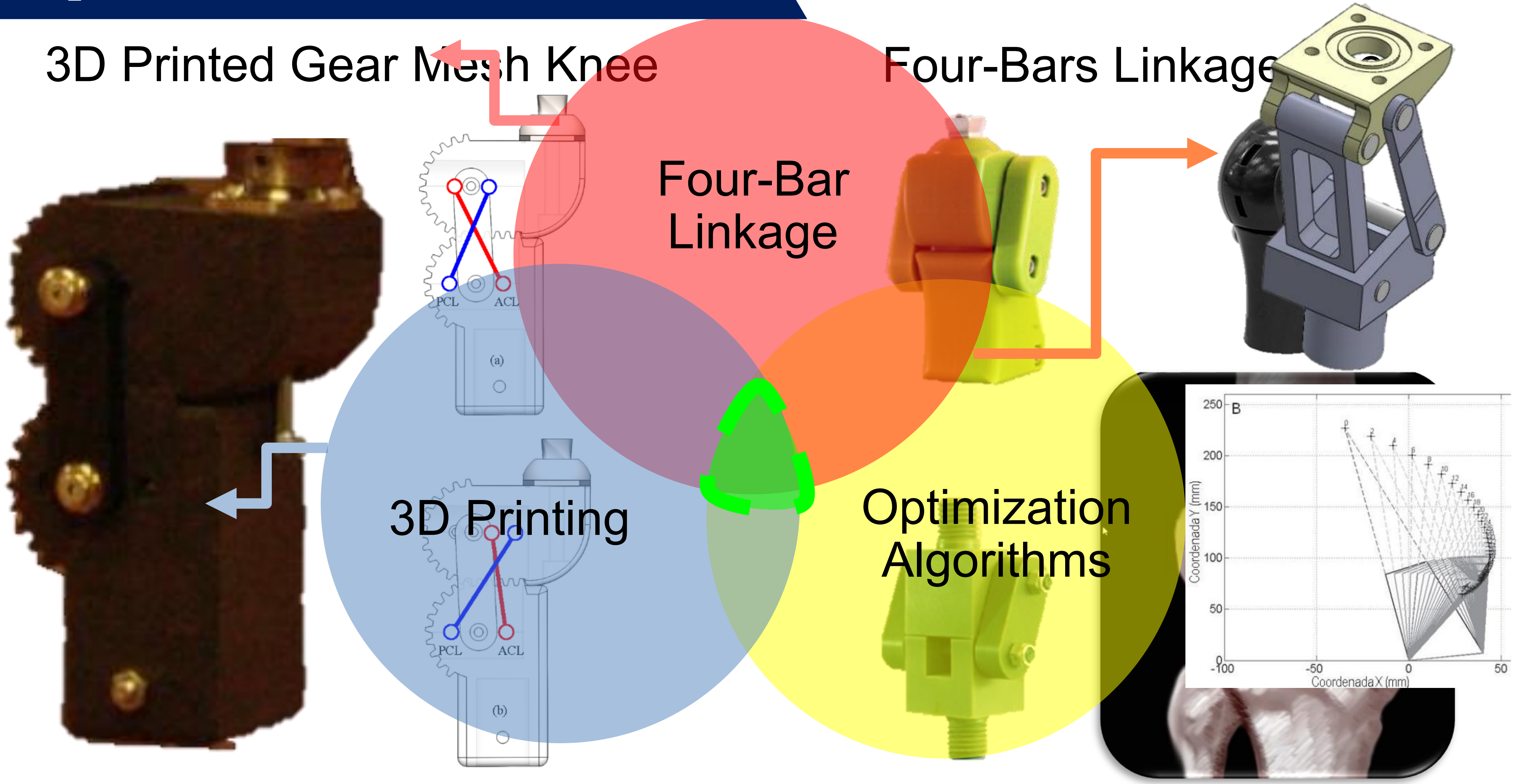
1 billion people live with disabilities in low- and middle-income countries, where access to healthcare and prosthetic services is severely limited.

Among them, 4 million are lower-limb amputees, many of whom lack access to affordable and functional prosthetic options.

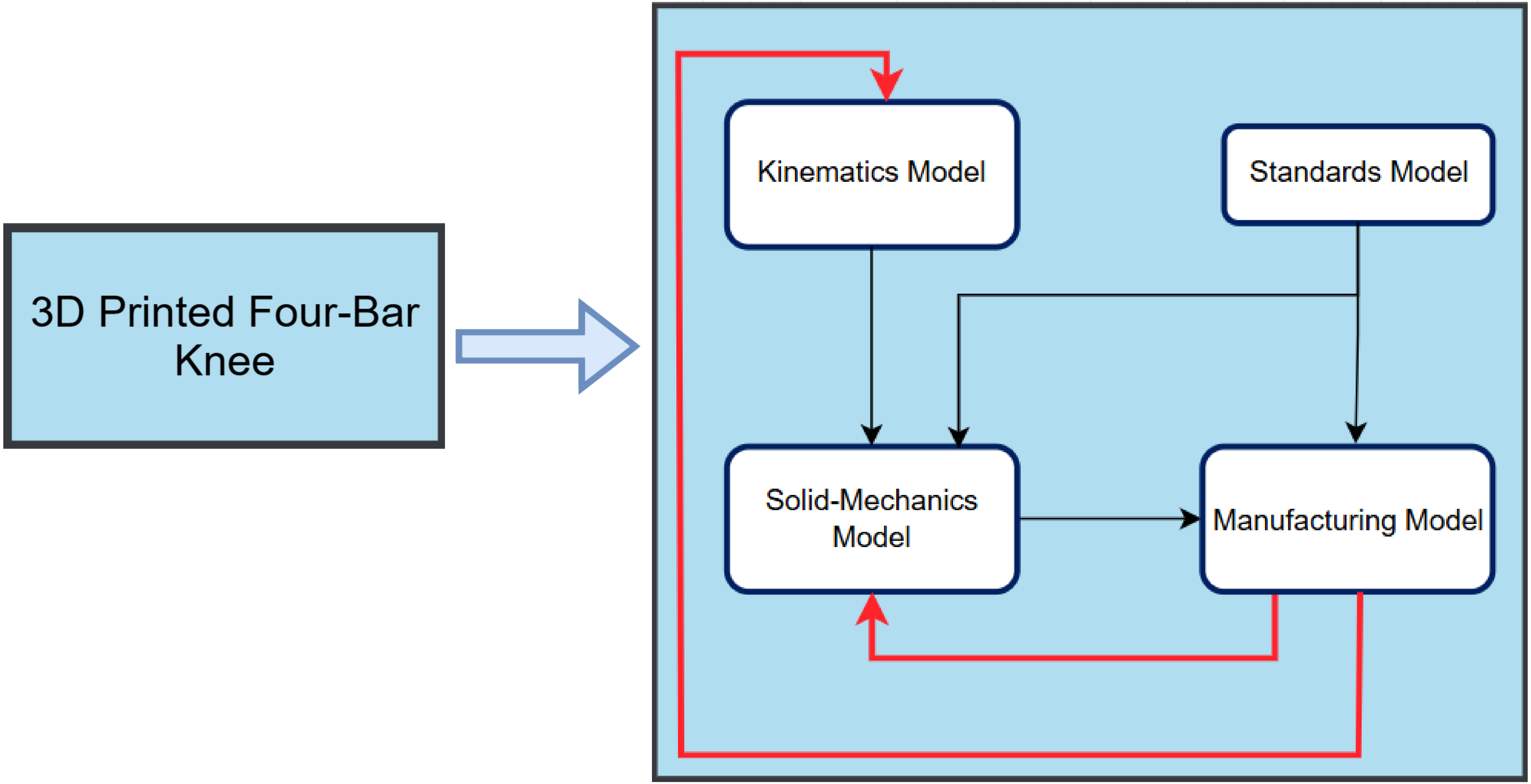
This project develops a low-cost, 3D-printed prosthetic knee, optimized through refined geometry, printable materials, and validation through FEA and prototyping.

Figure 1: World map of 3D printing hubs

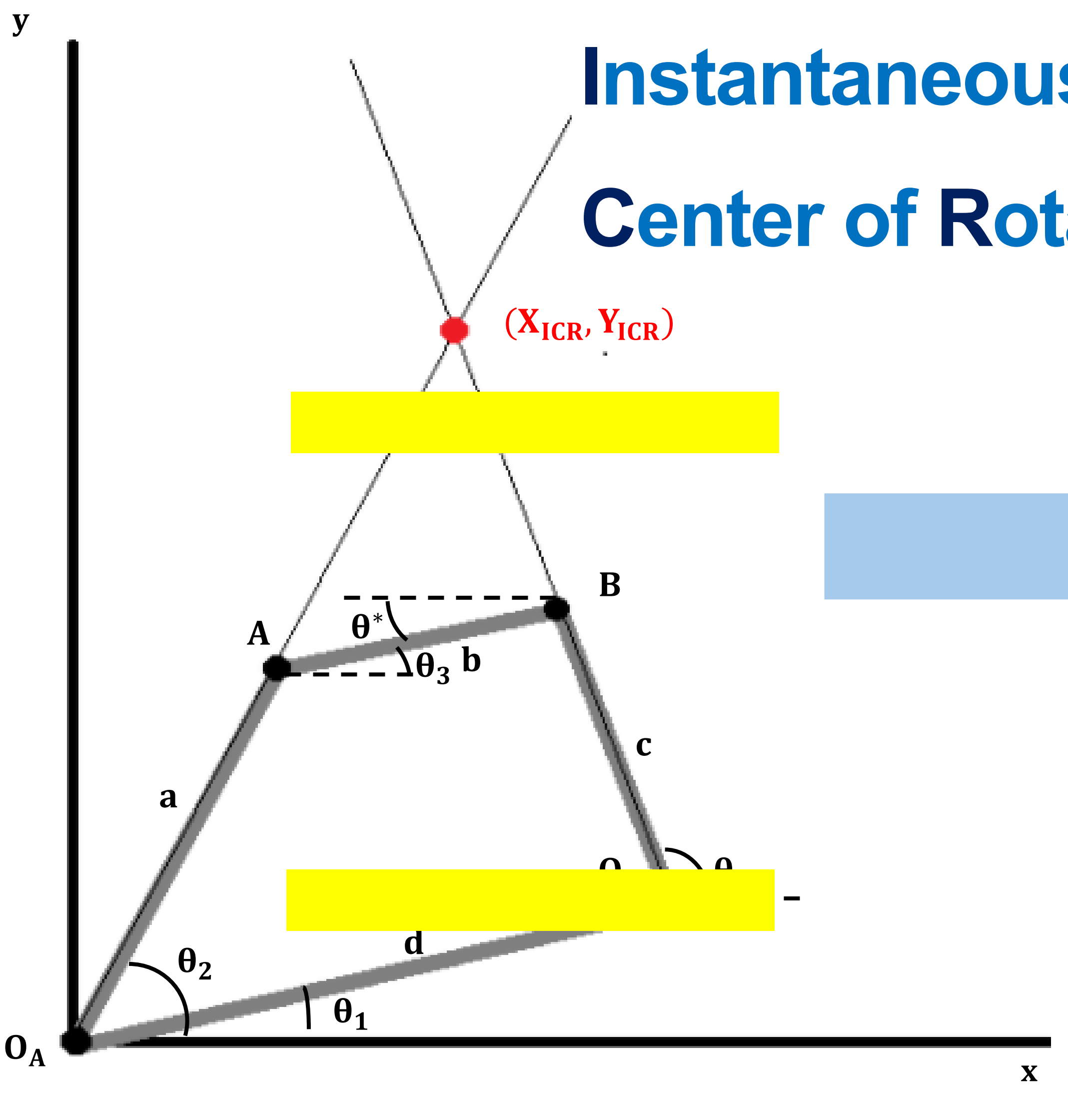
Proposed Solution



Plan of Action



Kinematic Analysis



Instantaneous Center of Rotation

Governing Kinematic Equations:

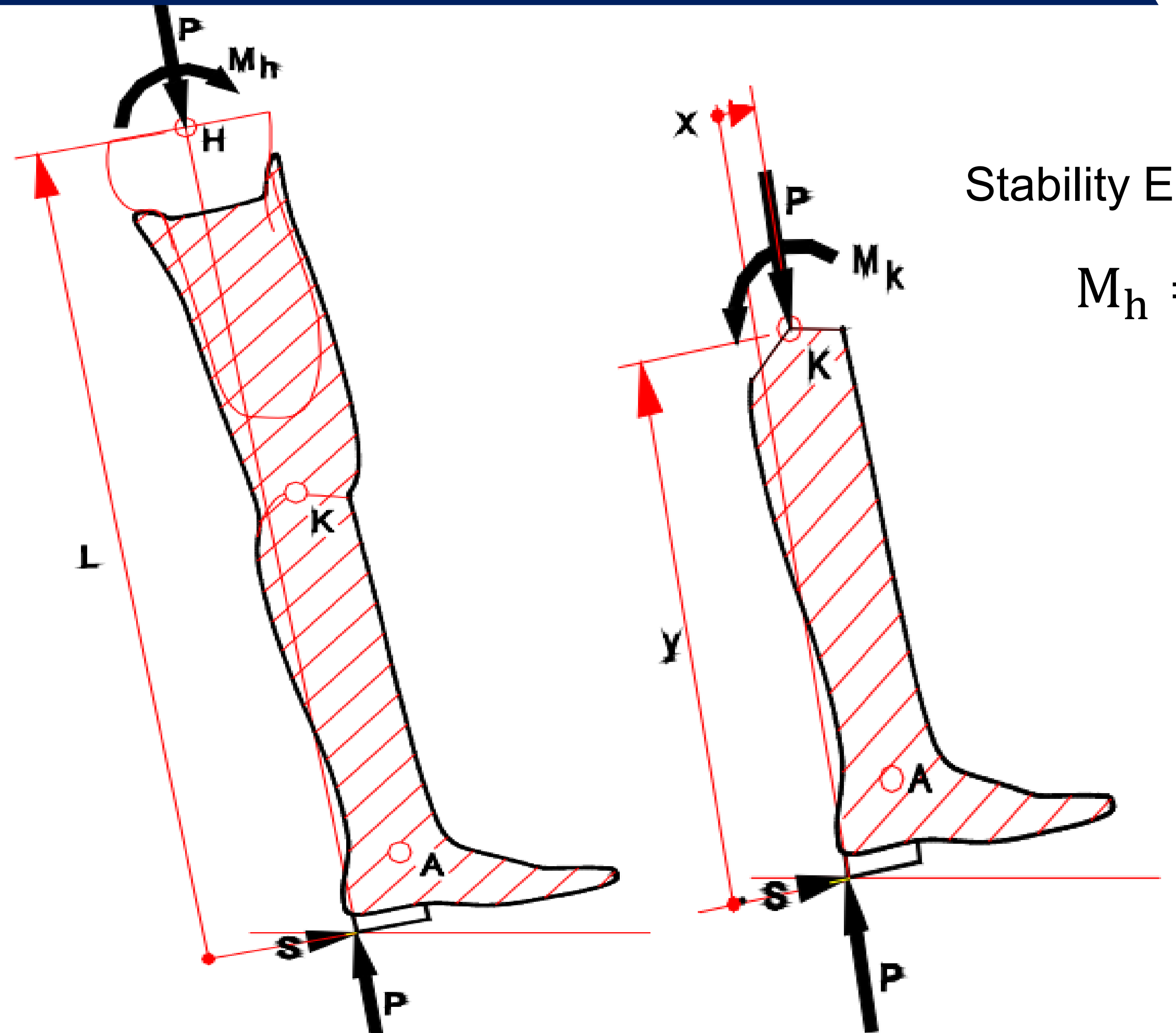
ICR Trajectory in the x-direction :

$$X_{ICR} = \frac{X_{O_B}\tan\theta_4 - Y_{O_B}}{\tan\theta_4 - \tan\theta_2} - d\cos\theta_1 - X_{O_B}$$
$$= f_1(a, b, c, d, \theta_1, \theta_2, \theta_R, \theta^*)$$

ICR Trajectory in the y-direction :

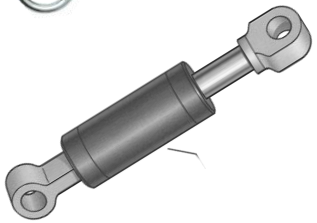
$$Y_{ICR} = \frac{(X_{O_B}\tan\theta_4 - Y_{O_B})\tan\theta_2}{\tan\theta_4 - \tan\theta_2} - d\sin\theta_1 + Y_{OB}$$
$$= f_4(a, b, c, d, \theta_1, \theta_2, \theta_R, \theta^*)$$

Ensuring Stability



Stability Equation:

$$M_h = \left(\frac{L}{y}\right)(Px - M_k)$$



$$M_h = PL\boxed{\left(\frac{x}{y}\right)}$$

~~M_k = Moment from Extension System~~

P = Axial Load Force

L = Distance Hip − Point of Contact

M_k = Moment from Extension System

= Distance ICR − Load Line

- **Remove Extra Extension System.**
- **Minimize x/y ratio.**

Ensuring Control

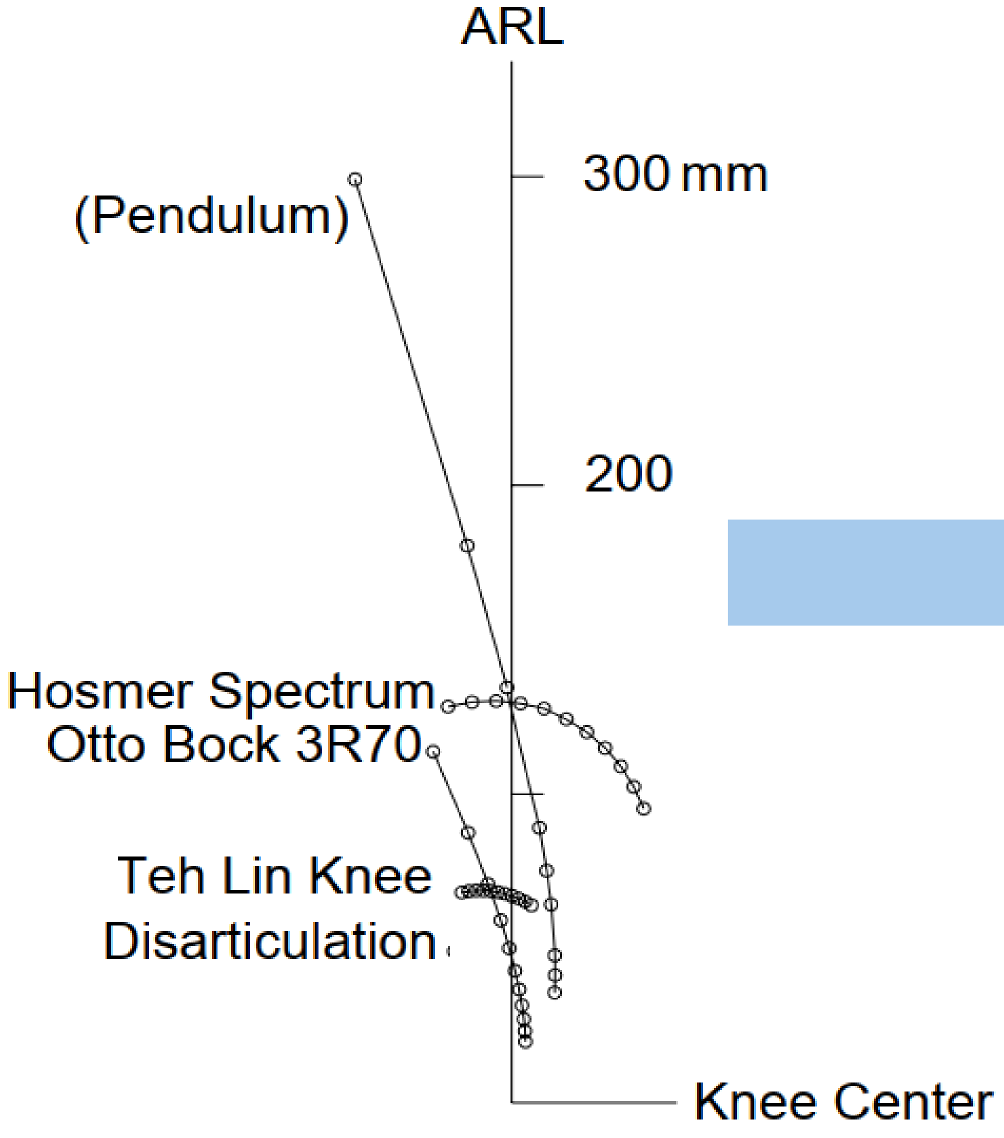


Figure 2: ICR Trajectories for Different Knees

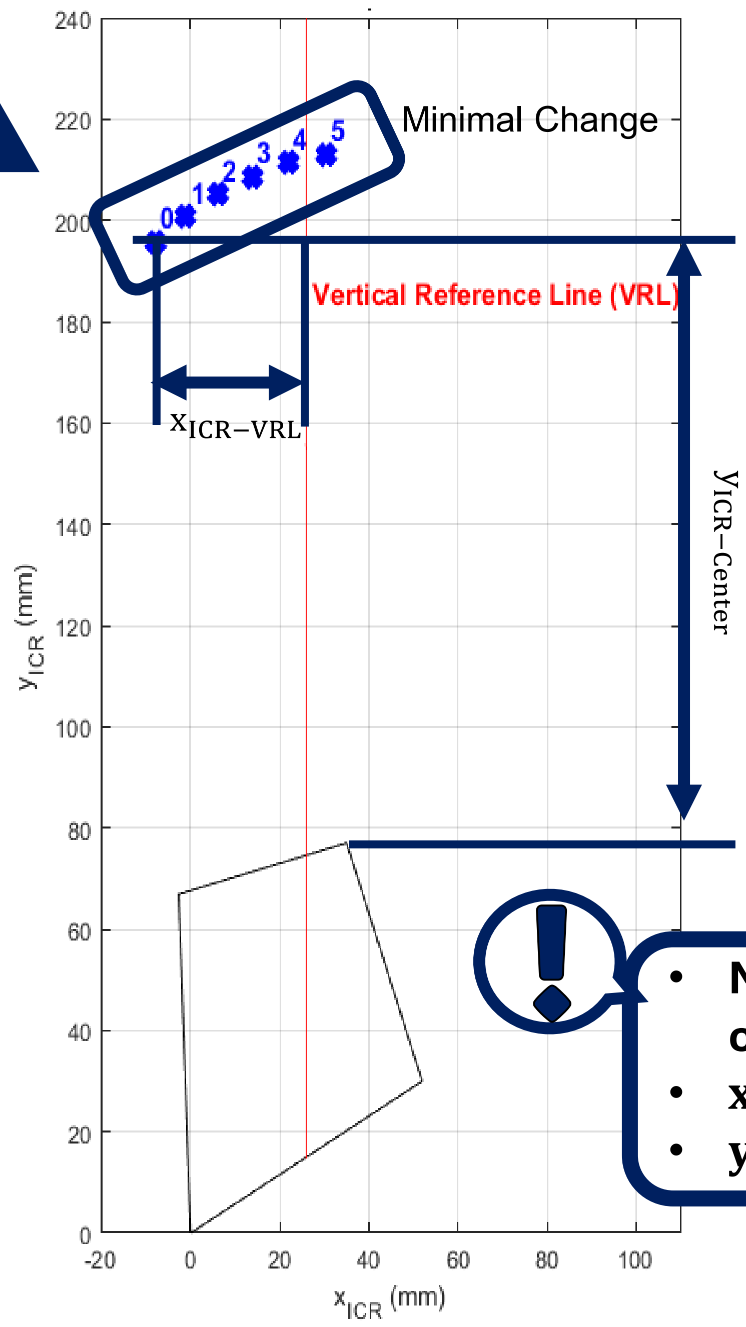


Figure 3: Metrics for Stability

- Minimal ICR´s height change in 5° of flexion
- $x_{ICR-VRL} \geq 6$ mm
- $y_{ICR-Center} \geq 100$ mm

Trajectory Selection

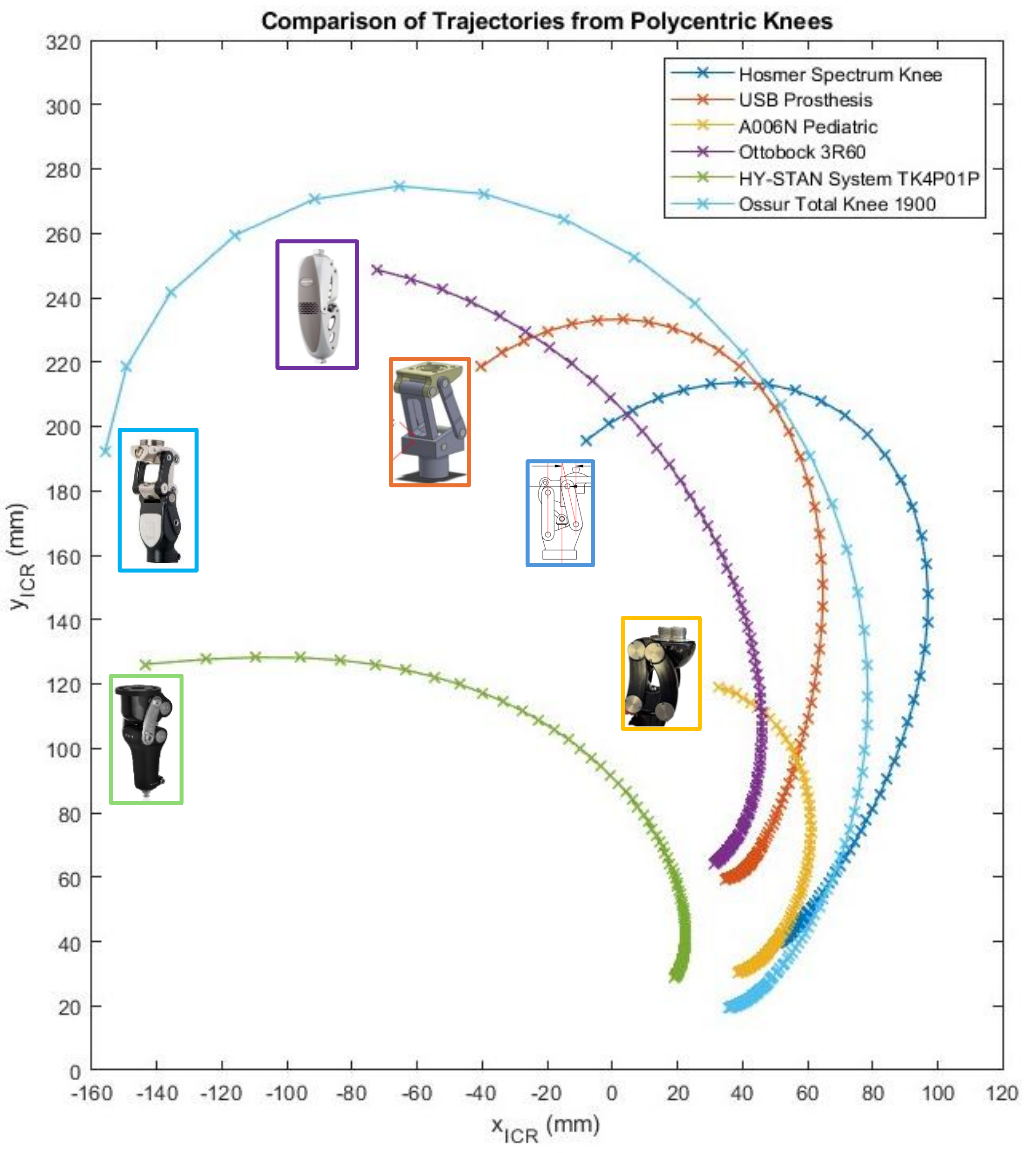


Figure 4: Comparative Study of Knees from the Market

Knee	x-distance (mm)	y-distance (mm)
Hosmer Spectrum Knee	34	119
USB Prosthesis	60	123
A006N Pediatric	-17	66
Ottobock 3R60	93	157
HY-STAN System TK4P01P	158	95
Ossur Total Knee 1900	172	157

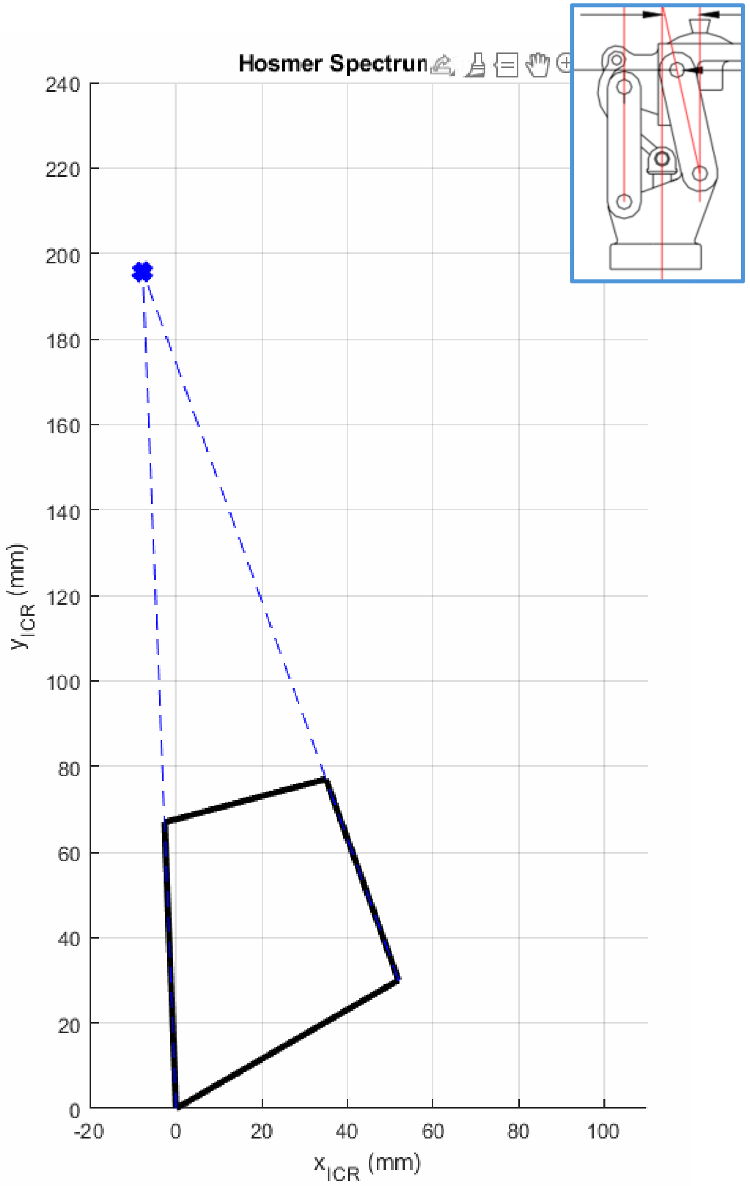
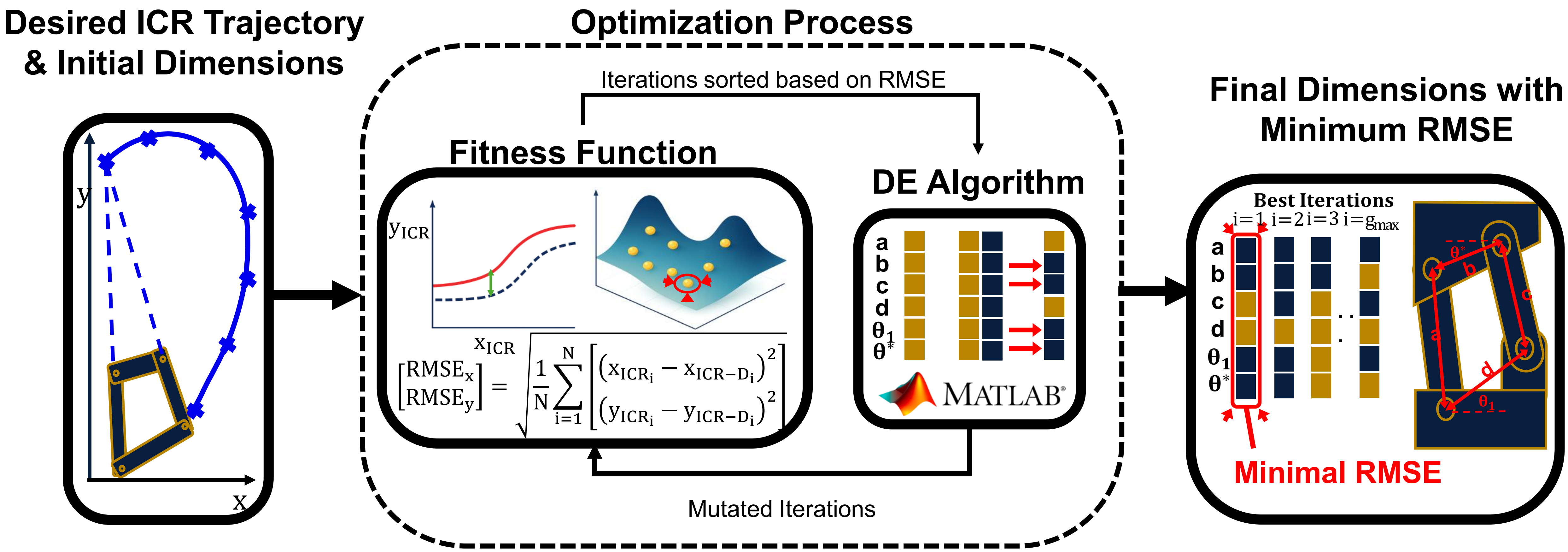
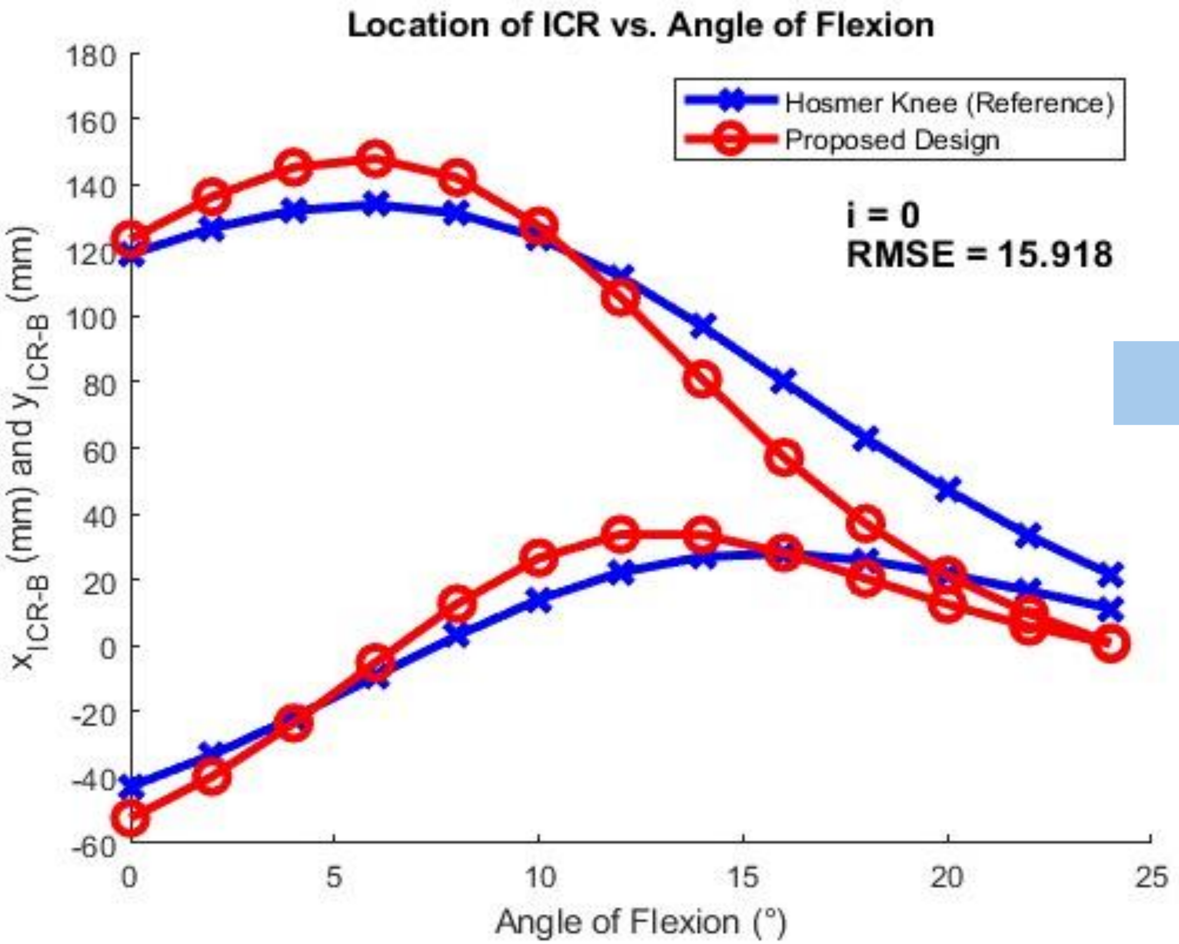


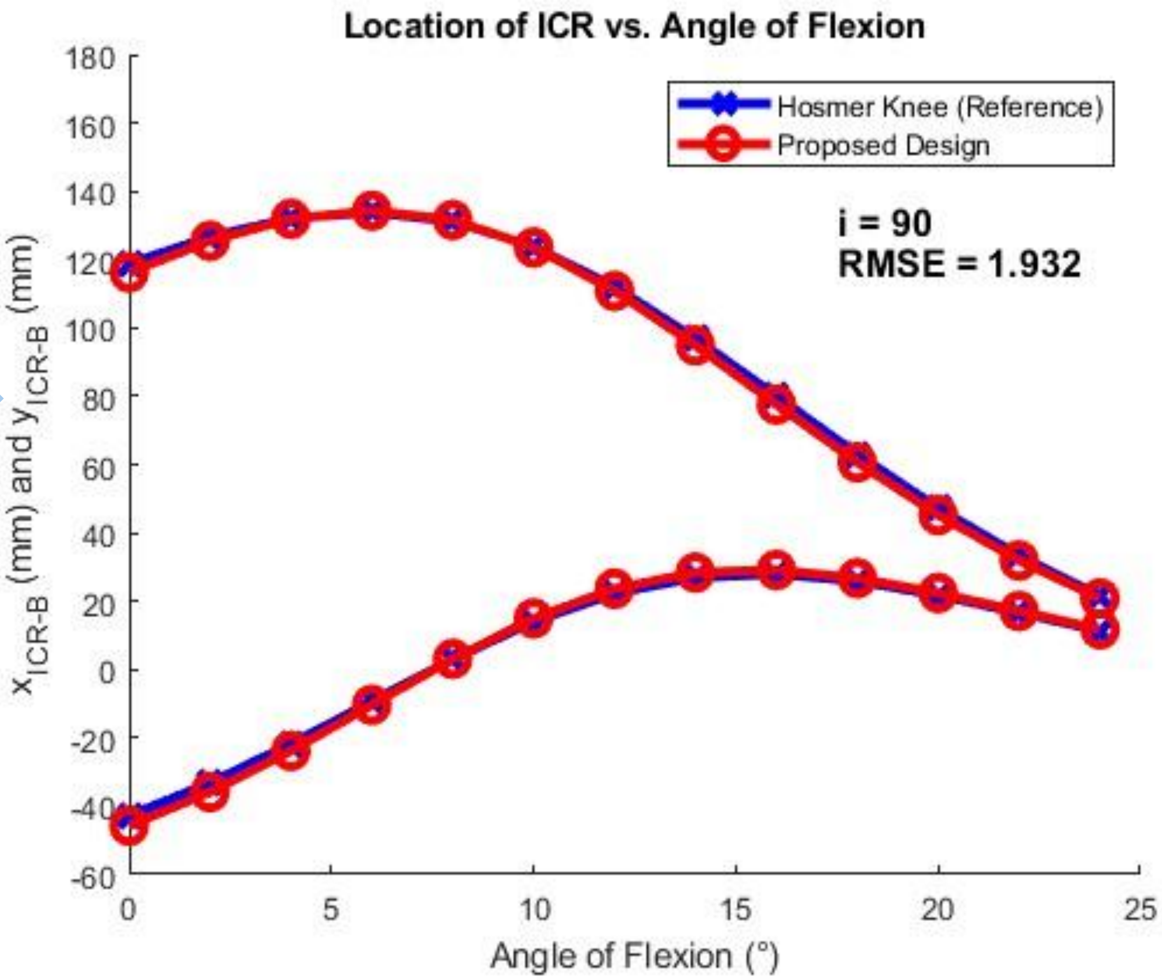
Figure 5: Hosmer Spectrum Knee ICR Trajectory

Kinematic Analysis



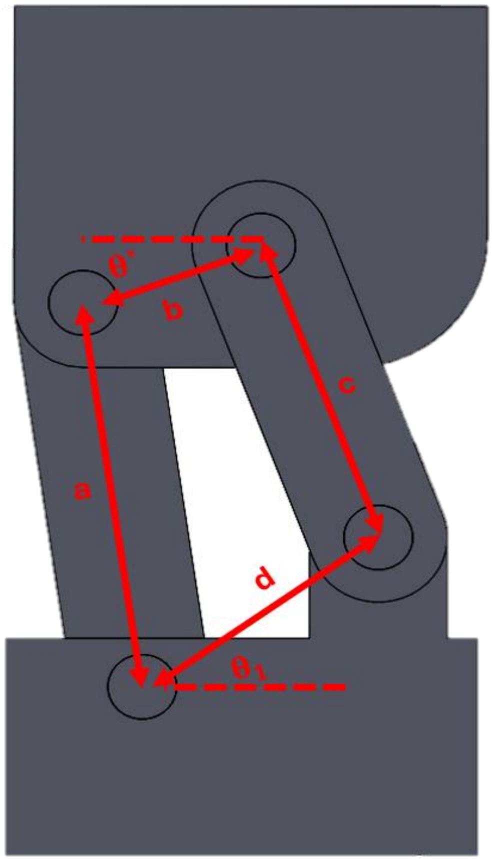
Kinematic Analysis

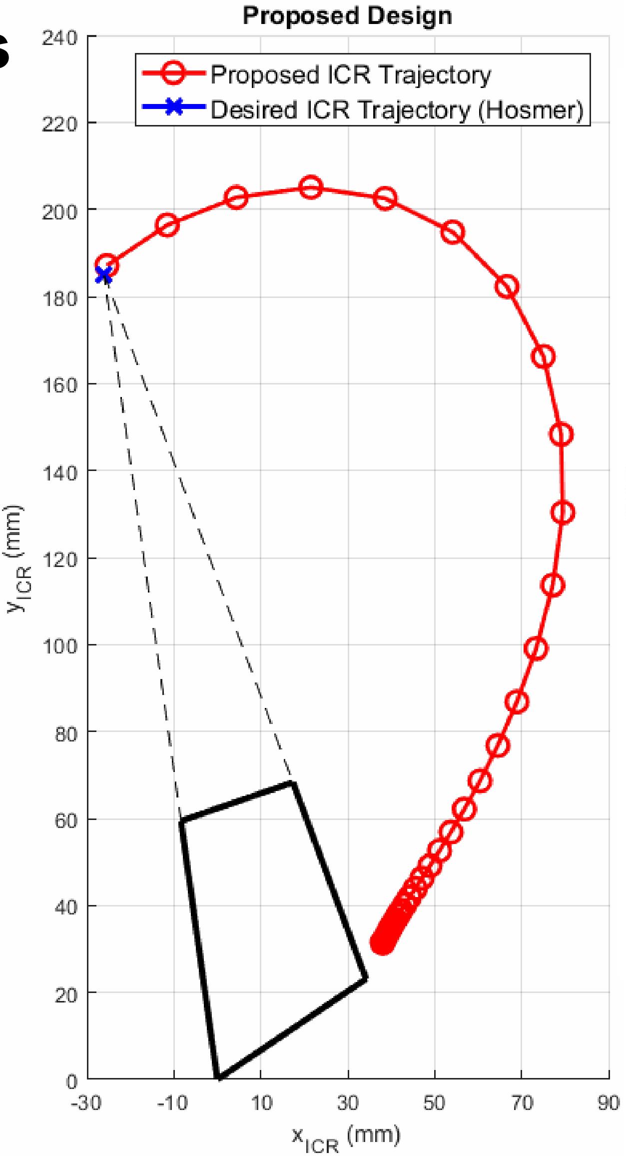




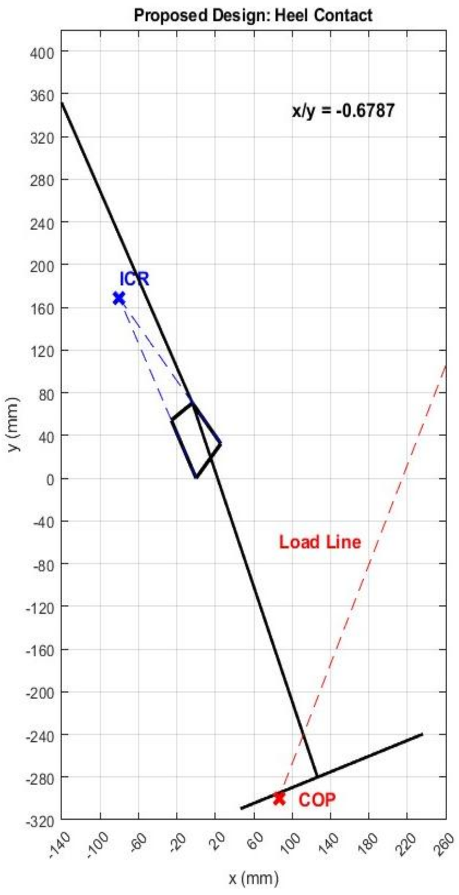
Kinematic Analysis

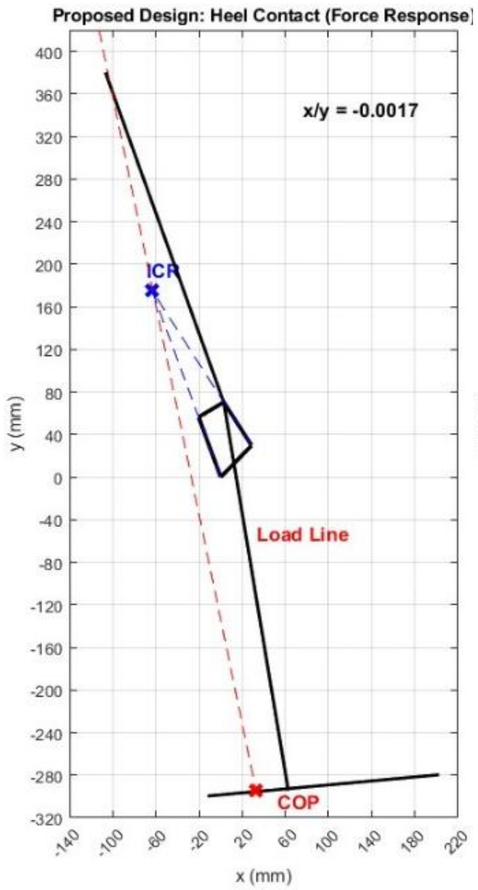
Final Dimensions

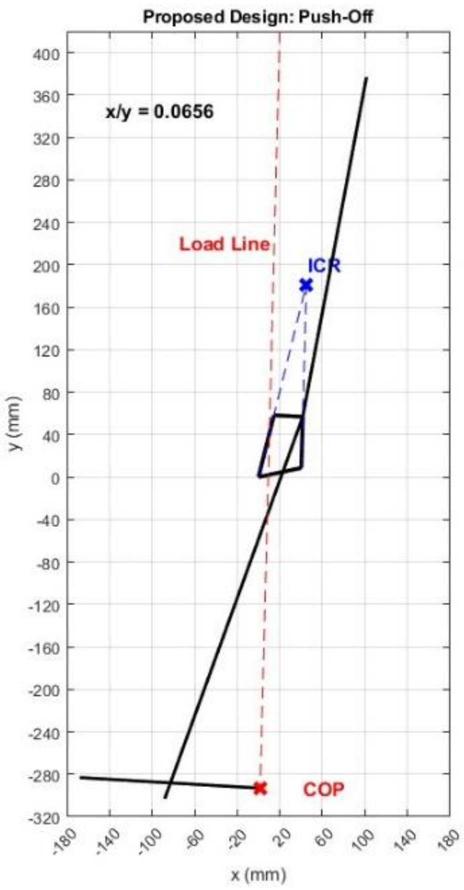




Stability Check







$\mathbf{a = 60.00\ mm}$	$\mathbf{c = 48.24\ mm}$	$\boldsymbol{\theta_1 = 34.04^\circ}$
$\mathbf{b = 27.24\ mm}$	$\mathbf{d = 41.26\ mm}$	$\boldsymbol{\theta^* = 19.06^\circ}$

PLA Experiment

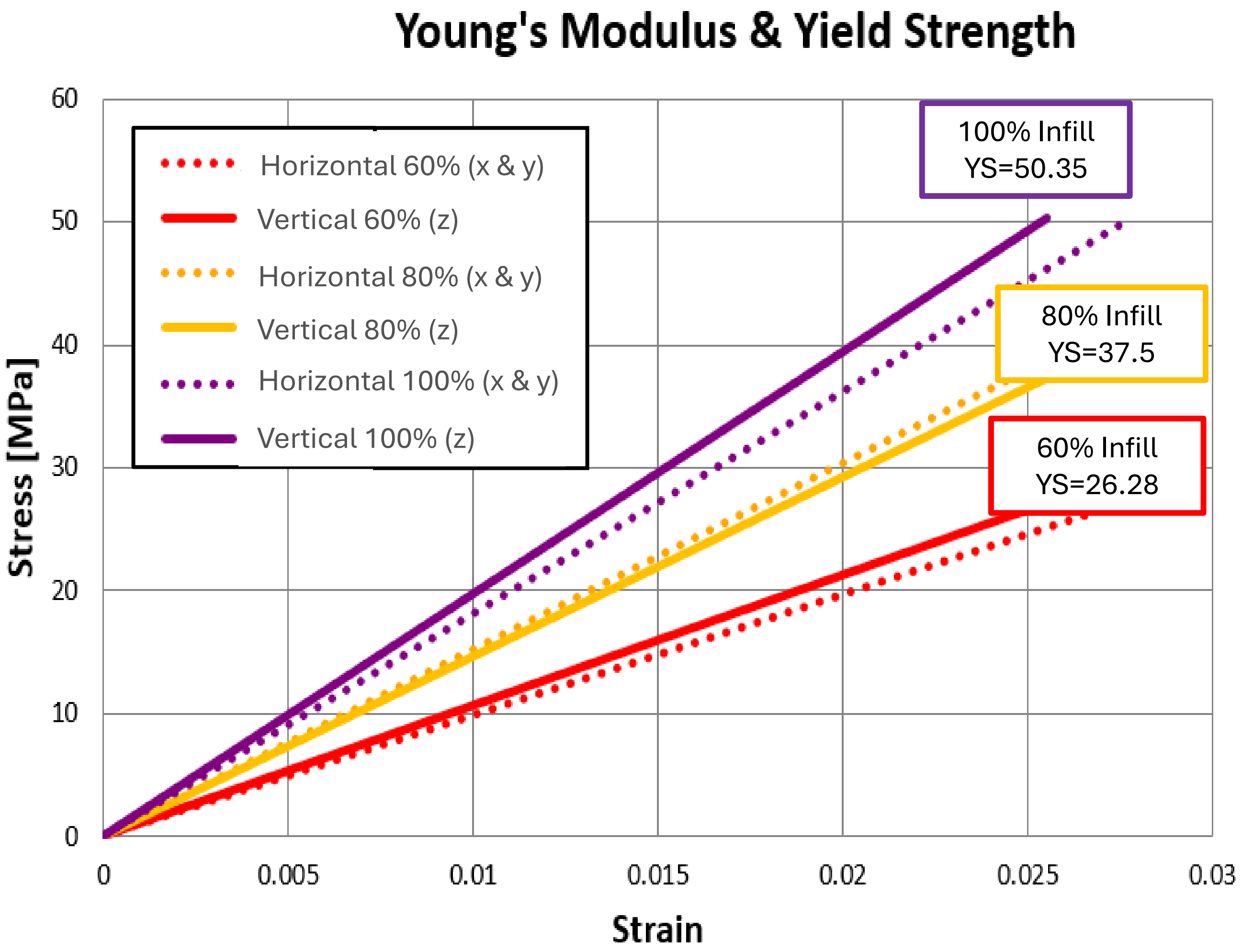


Figure 6: Mechanical Properties from PLA of Best Trials

Figure 7: MTS Criterion C43

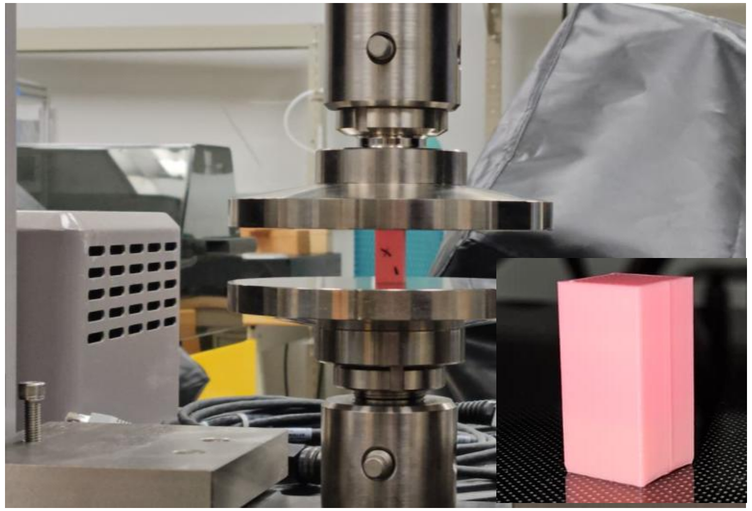
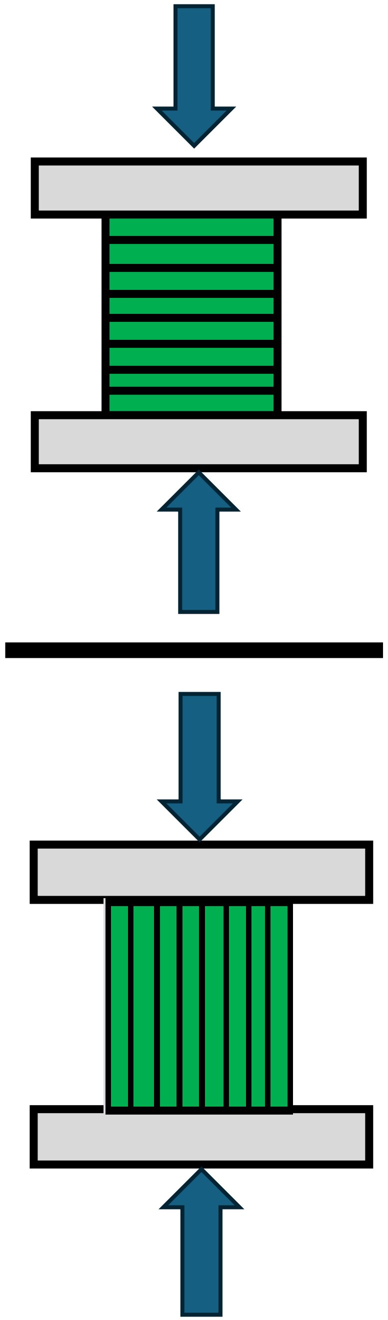
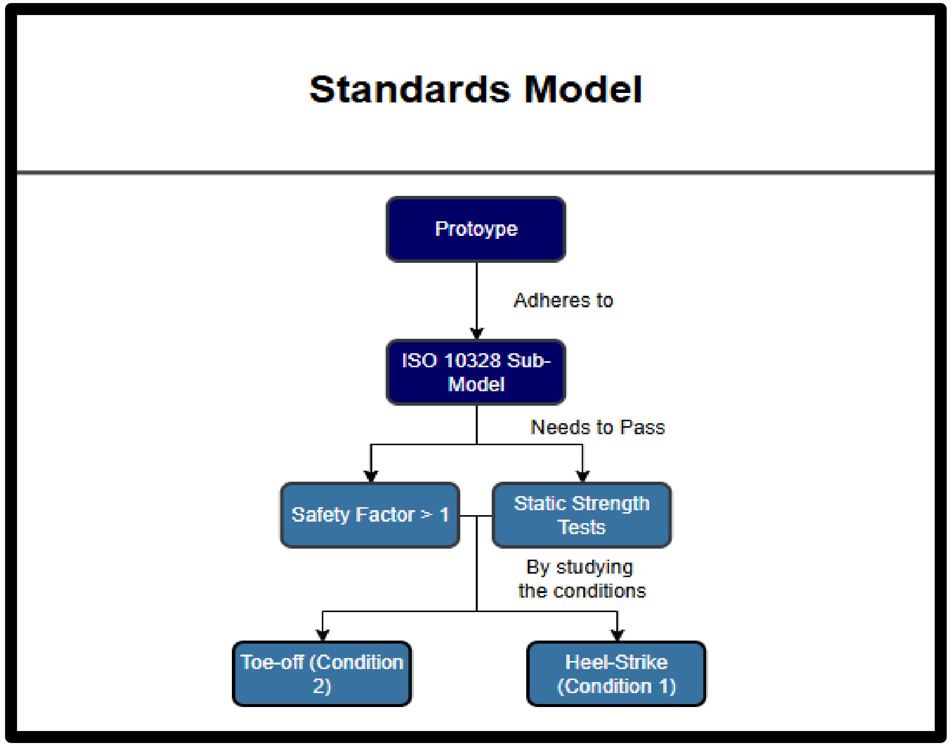


Figure 8: Compression on PLA



**Polylactic Acid

Standards Model



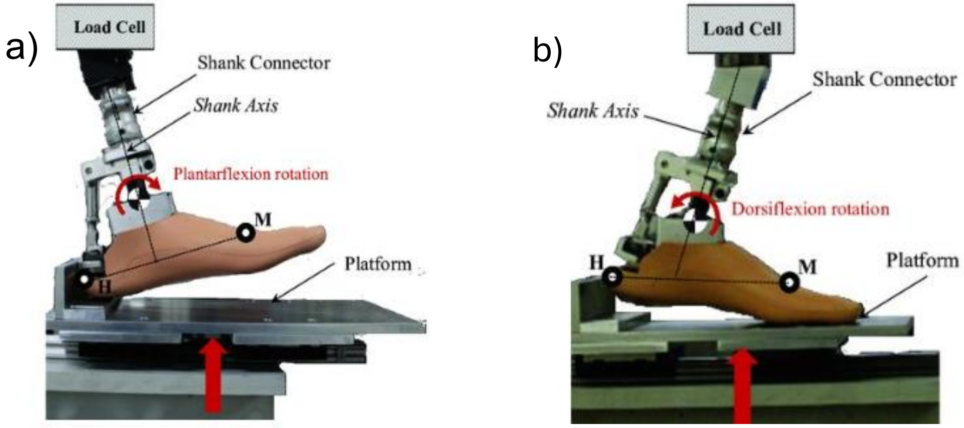


Figure 8: ISO 10328 a) Condition 1 and b) Condition 2

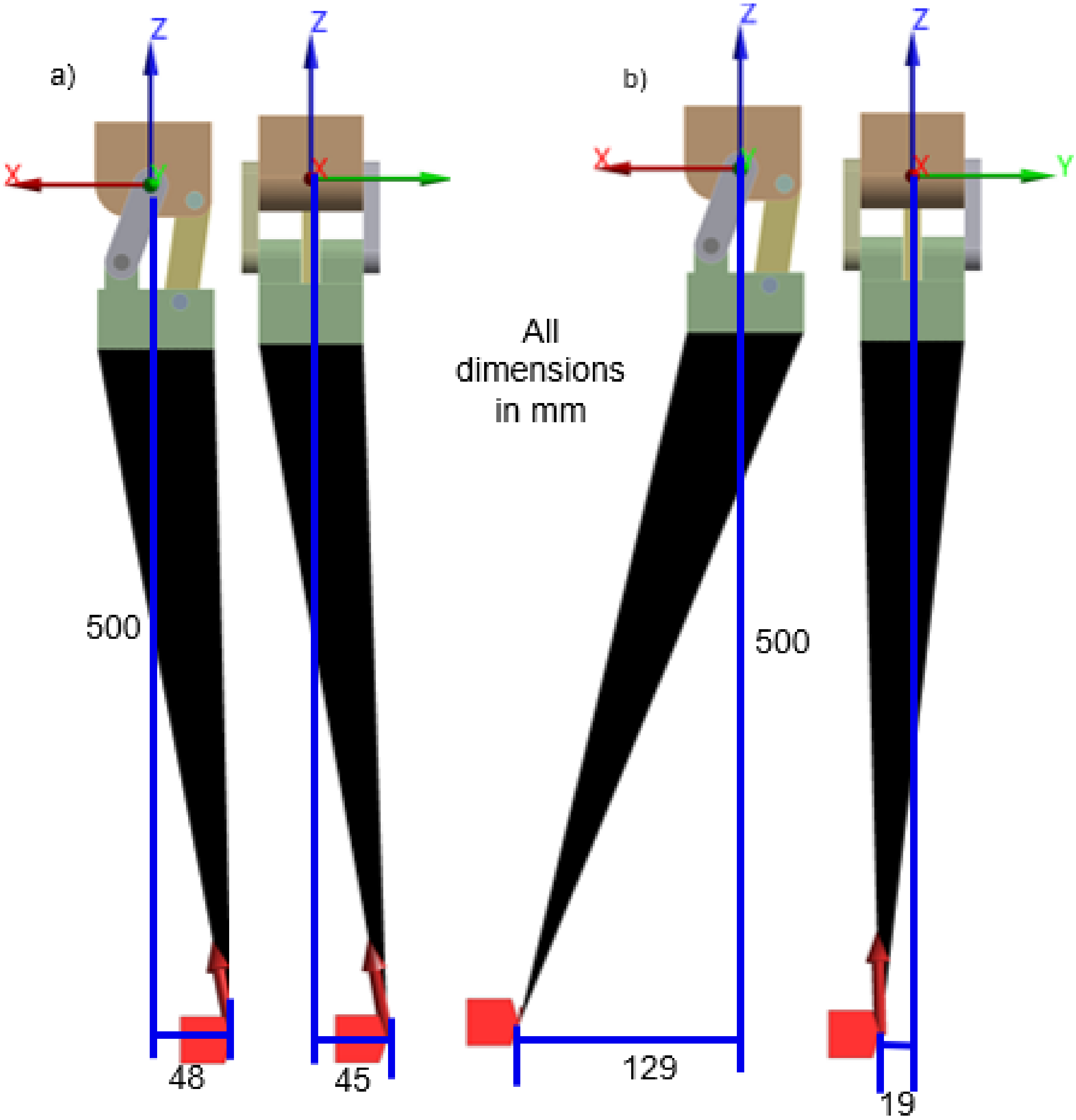
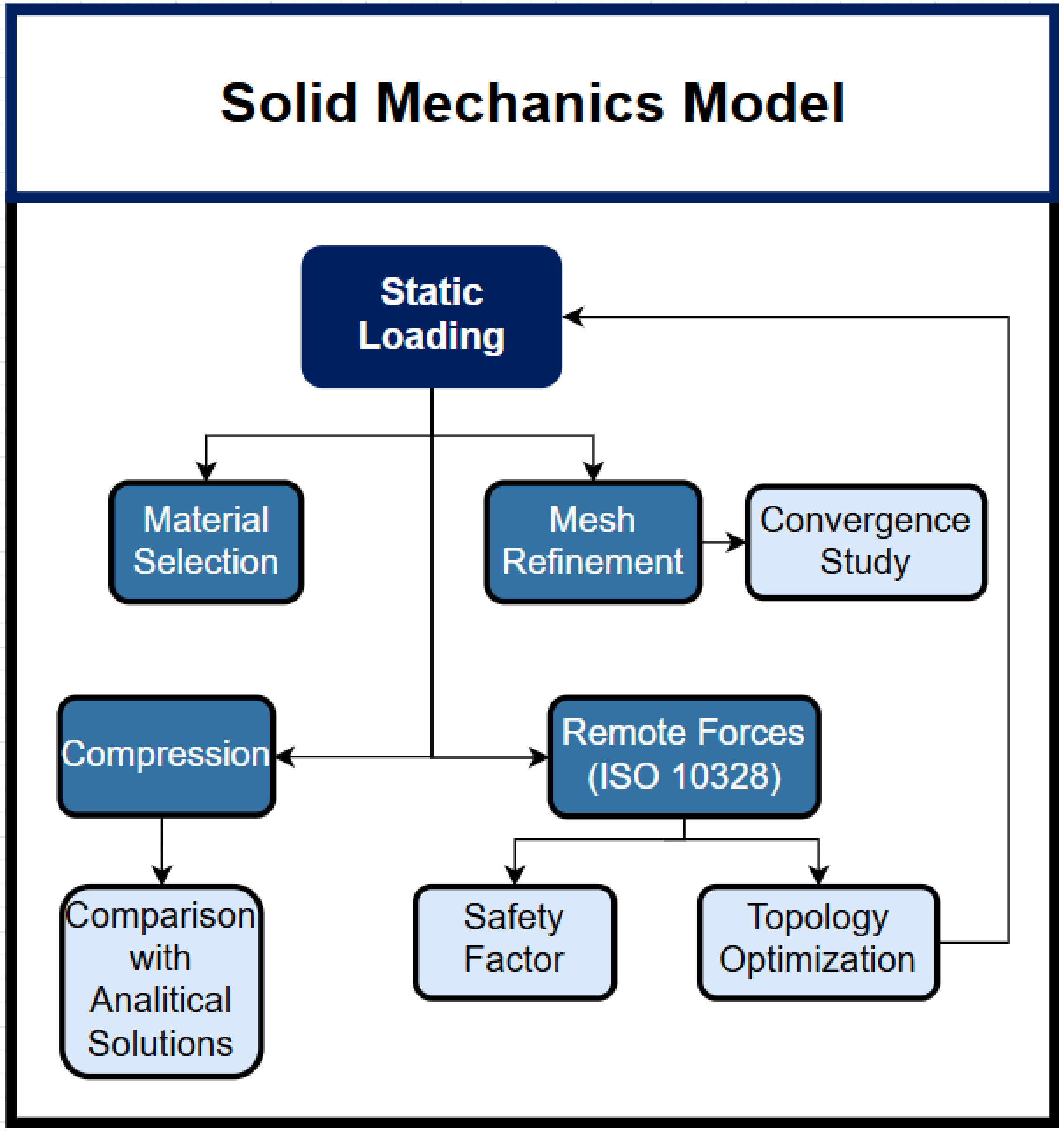


Figure 9: ISO 10328 Offsets. (a) Condition 1 & (b) Condition 2

Finite Element Analysis



Property	PLA	18-8 Stainless Steel
Young's Modulus [GPa]	2.94	193
Poisson's Ratio	0.33	0.29
Yield Strength [MPa]	50.35	207

Mesh Settings:

- Mesh Method: Tetrahedral, Quadratic
- Final Mesh Size: 1.2 mm
- Pins axially Constrained

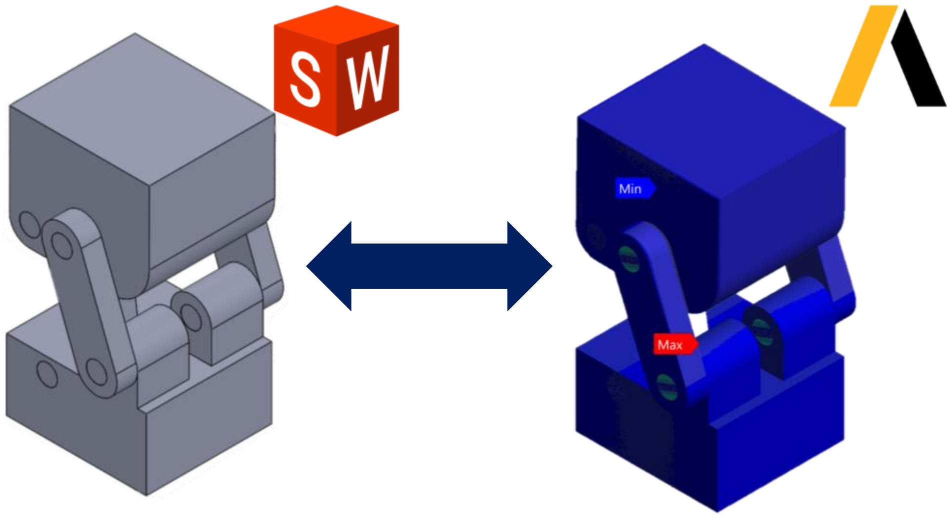
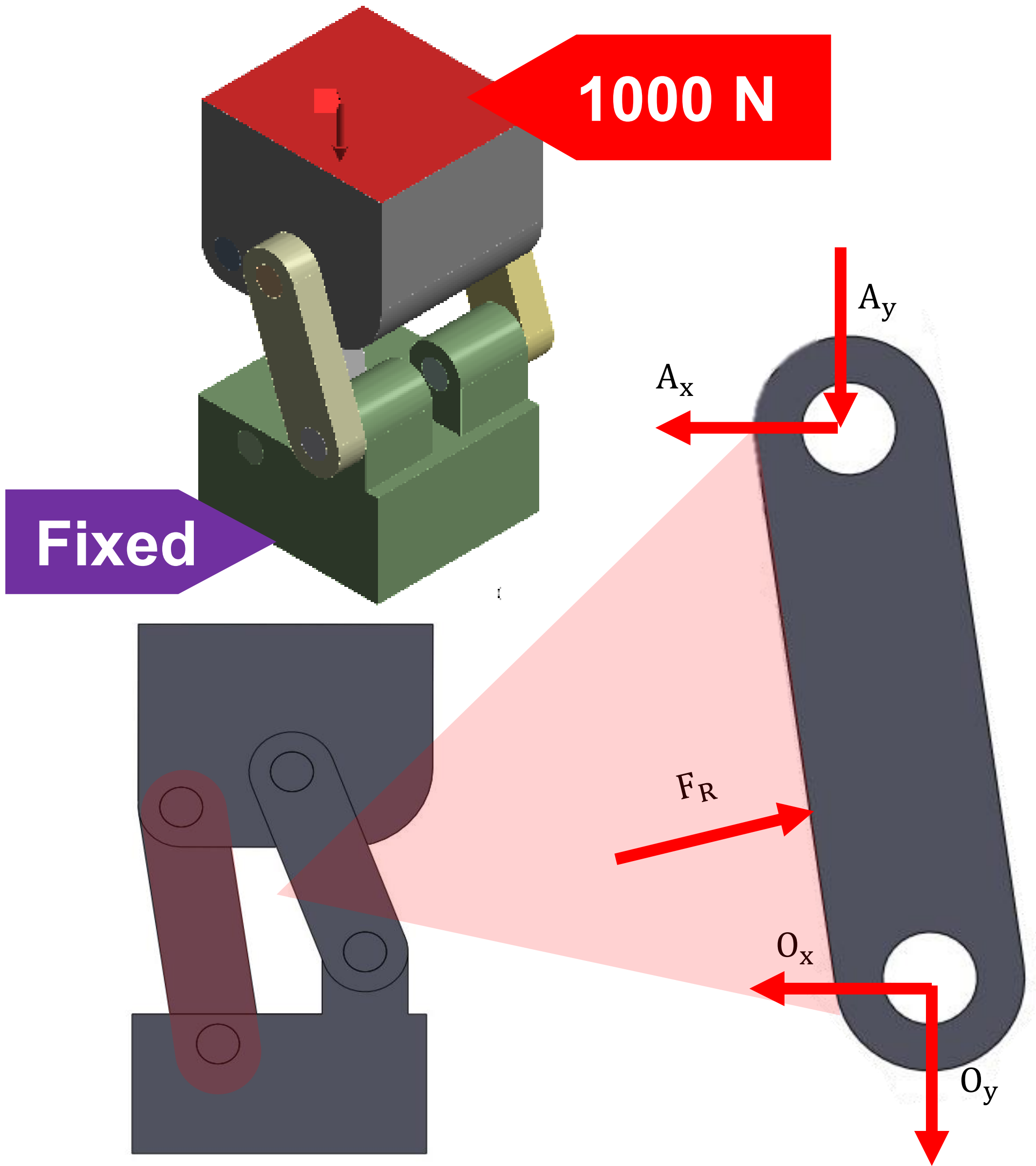
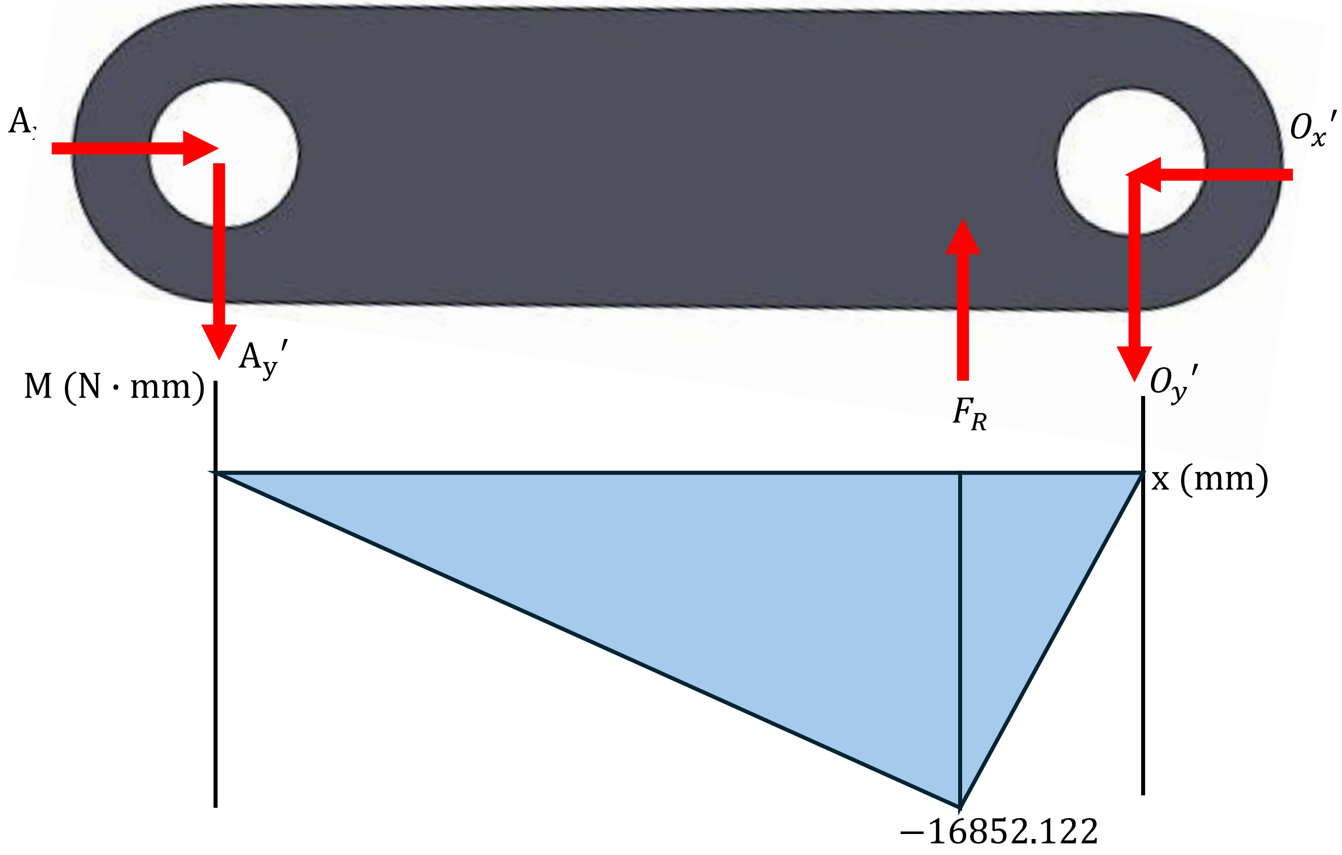


Figure 10: Preliminary Design

Compression



Central Bar Results:



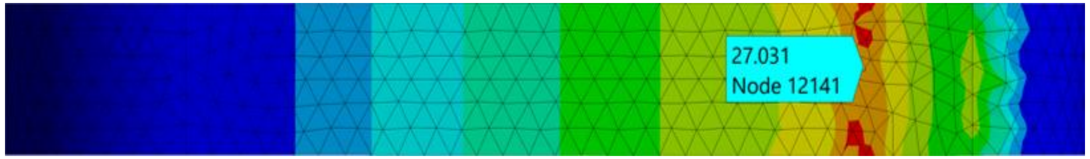
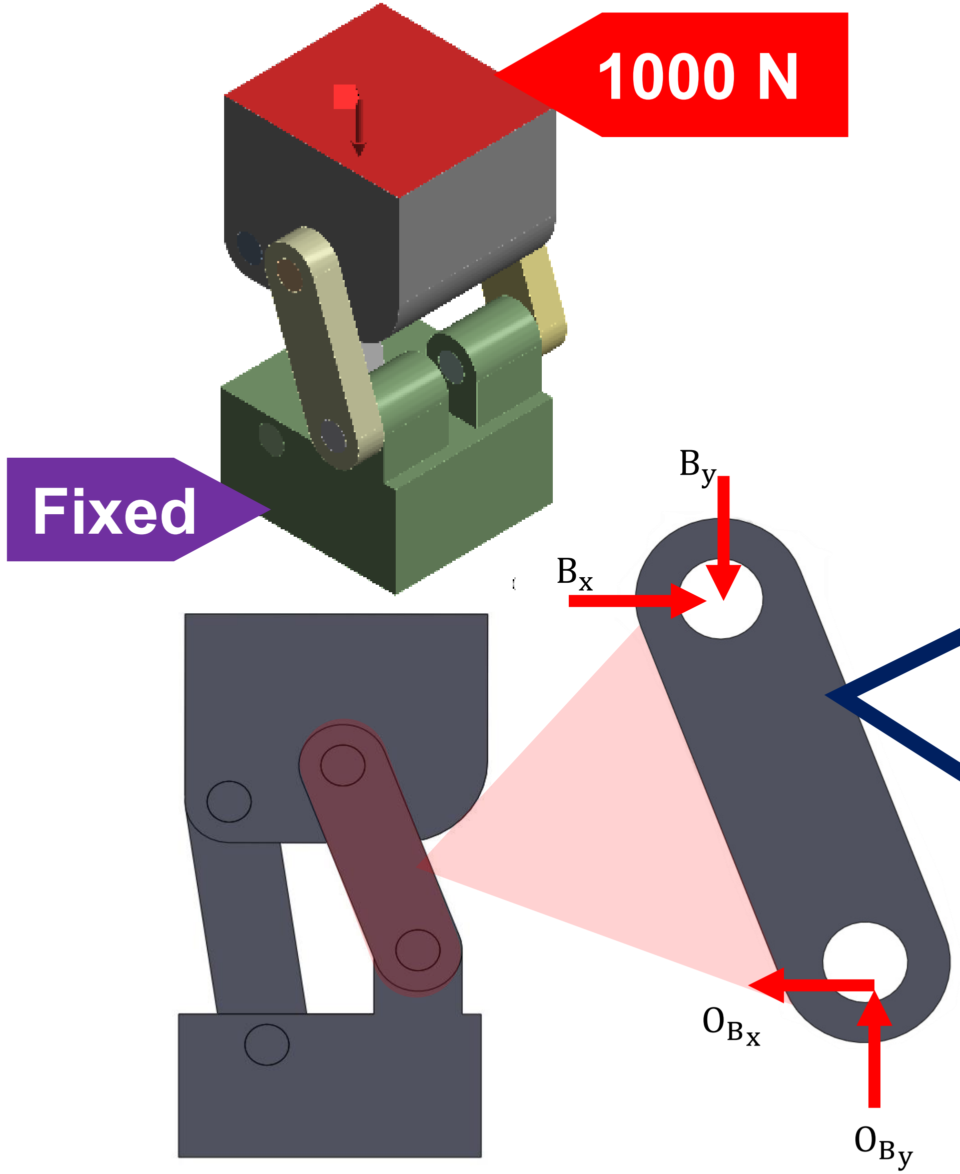


Figure 11: Moment Diagram from Central Bar

- **Proper distribution of stresses in FEA simulation.**
- **Error of 6.97% on FEA when compared with analytical calculations.**

Compression

Side Bars Results



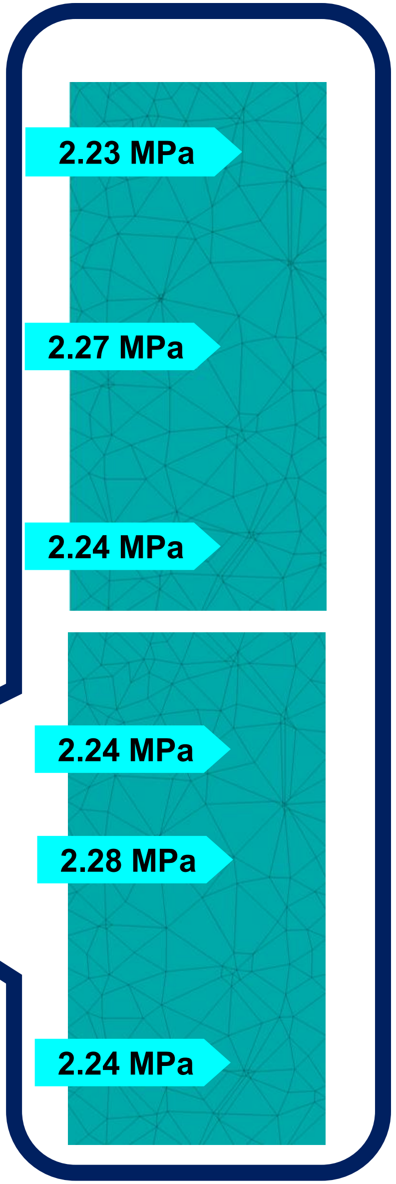


Figure 12: Stresses at Cross Sections from Side Bars

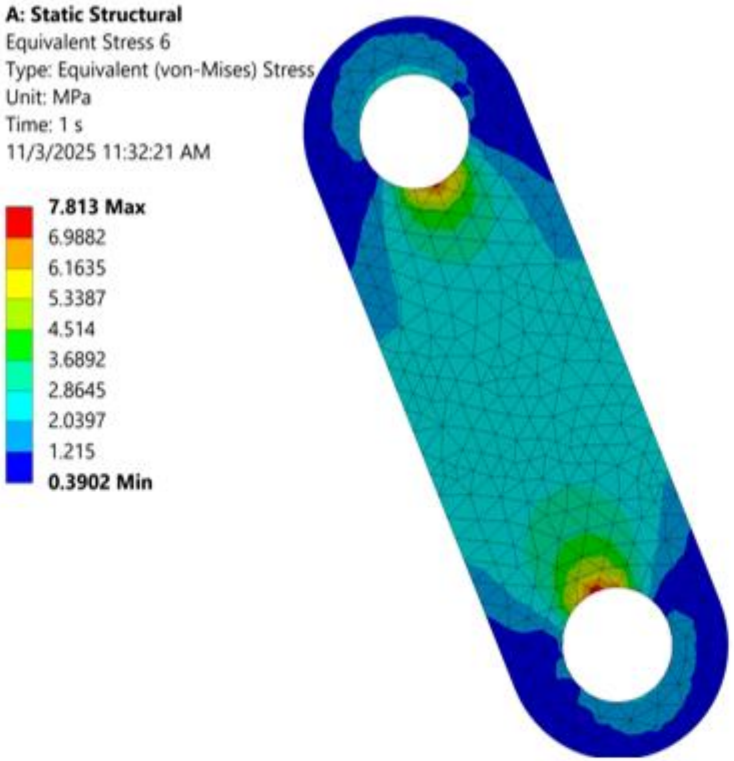


Figure 13: Stress Plot from Side Bar

- **Proper distribution of stresses in FEA simulation: showing bearing stress and stress concentration.**
- **Error of 0.247% on FEA when compared with analytical calculations.**

Oblique Forces

Required Design Modifications

- **Pins & holes:**
High bearing stress; thicken bars or increase pin/hole size.
- **Central bar:**
High bending/contact stress; increase width/thickness or raise stopper height.
- **Base:**
Local stress at bar contact; reinforce contact region.

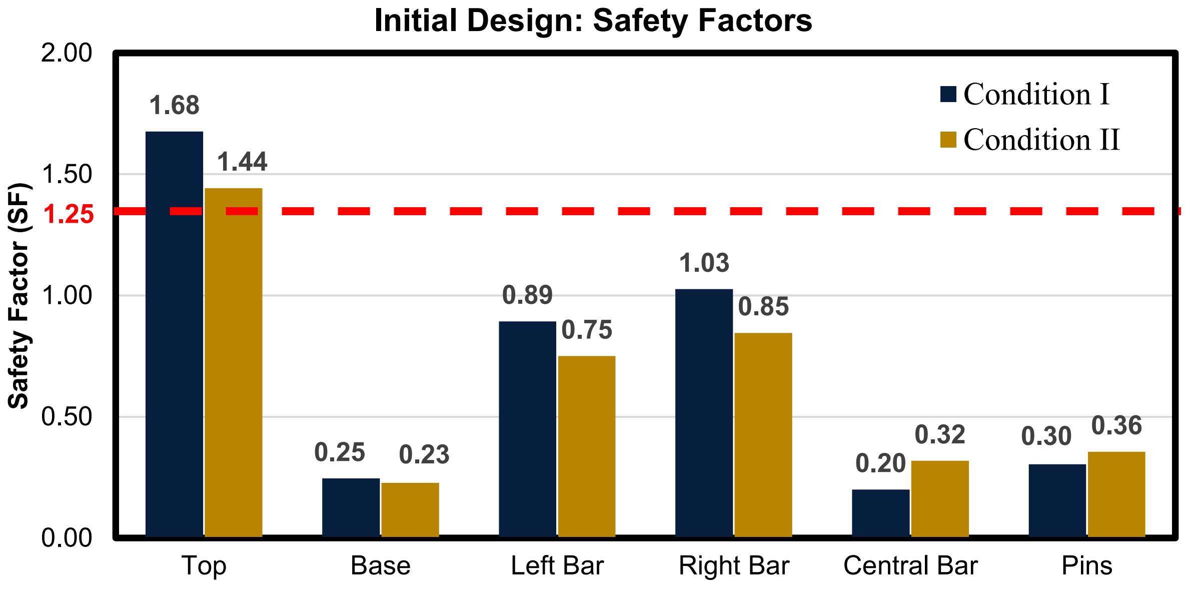


Figure 14: Safety Factors from Initial Design

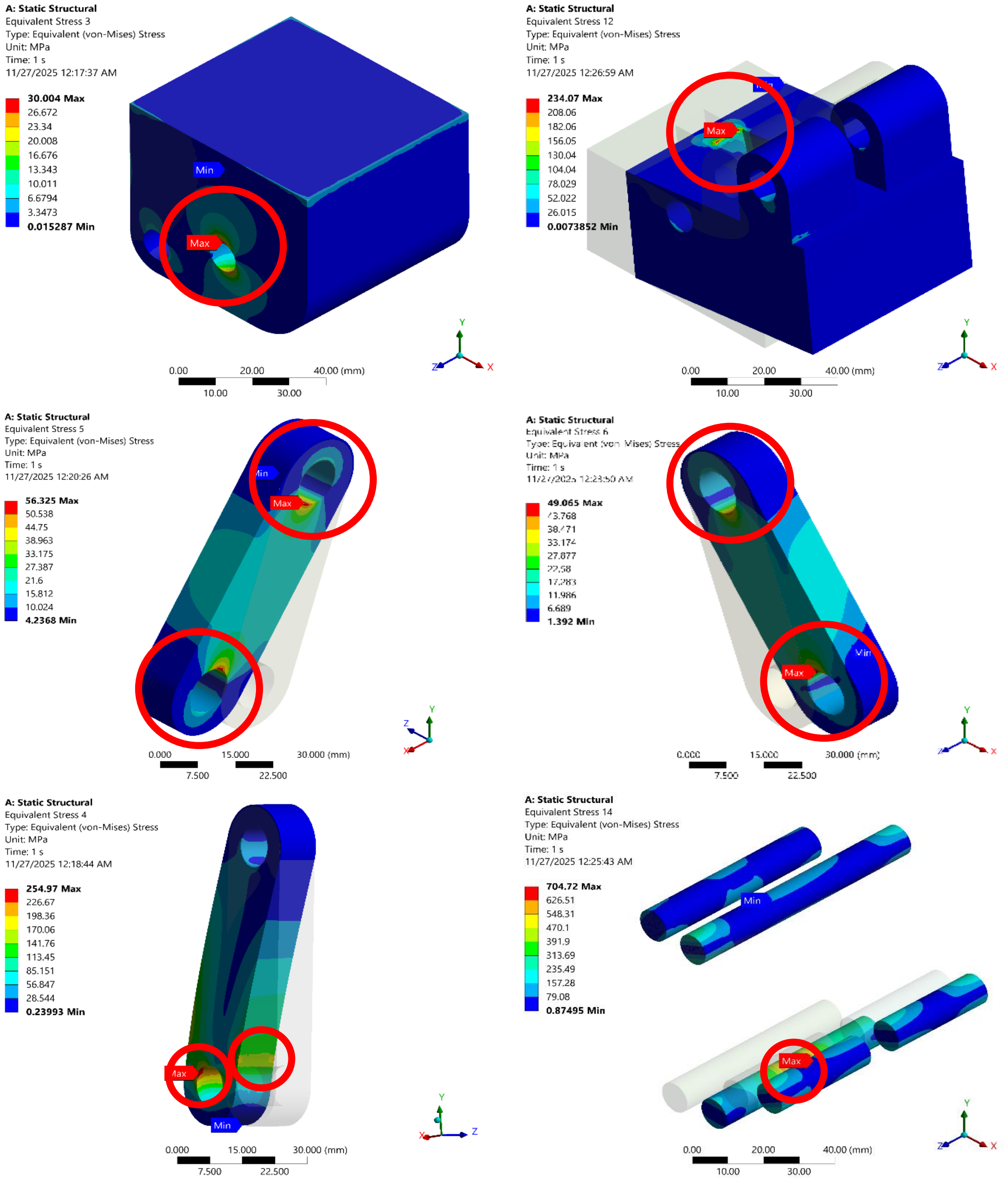


Figure 15: Stress Plots from each Individual Part (Condition 1)

Topology Optimization

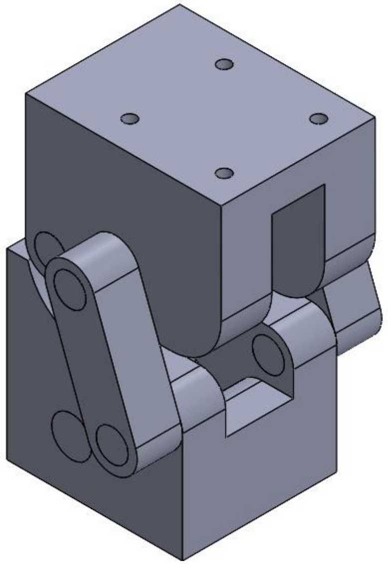


Figure 16: Design 2

- ✓ **Pins & holes:**
  Pin diameters increased from 10 mm to 12.7 mm (½ in) and 15.875 mm (⅝ in).
- ✓ **Central bar:**
  Increased thickness from… to
- ✓ **Base:**
  Increased height of stopper from to

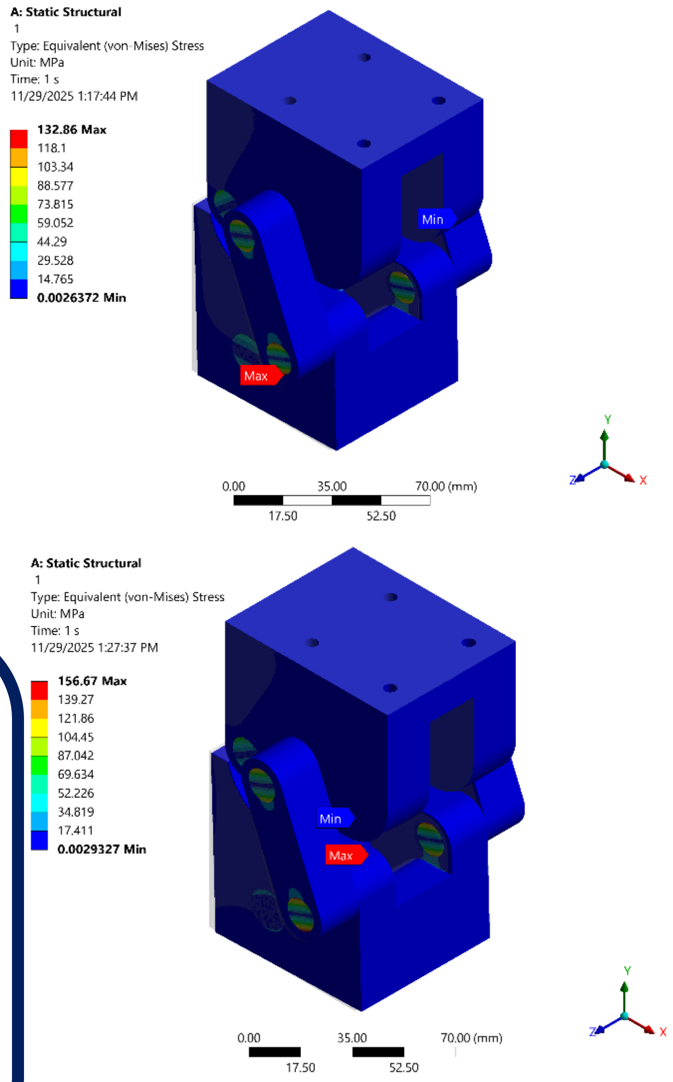


Figure 17: Stress Plots for Design 2.
a) Condition 1 & b) Condition 2

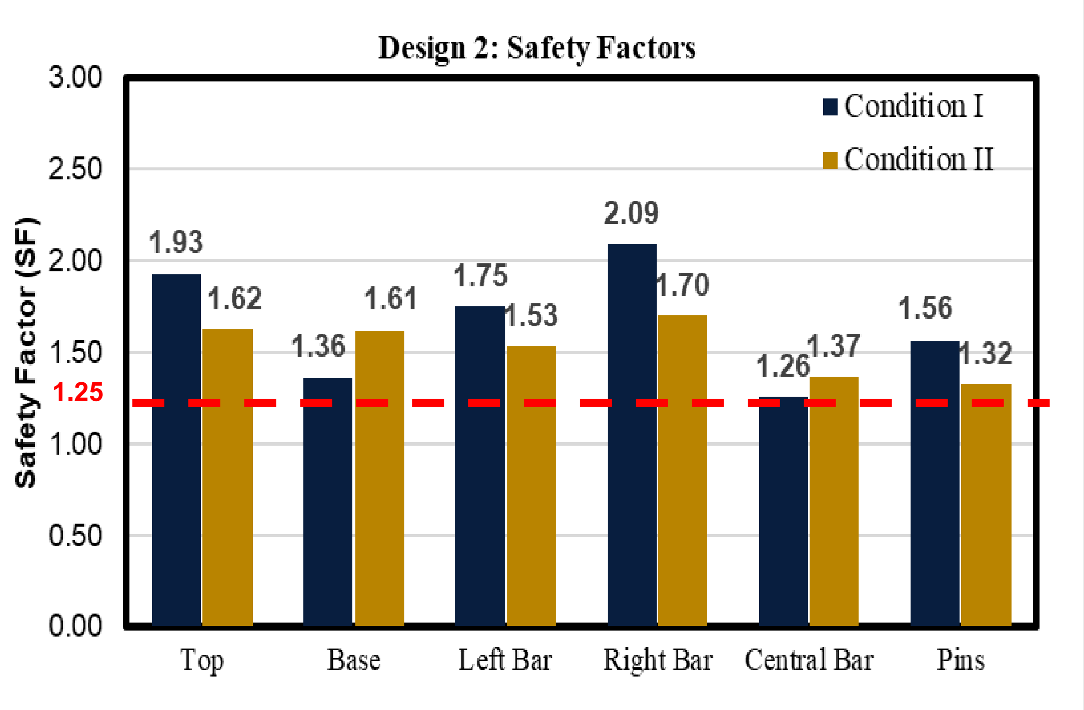


Figure 18: Safety Factors from Design 2

- ❑ Sections with safety factor exceeding 1.25, making possible the removal of material to satisfy:

  Weight ≤ 80 kg

Topology Optimization

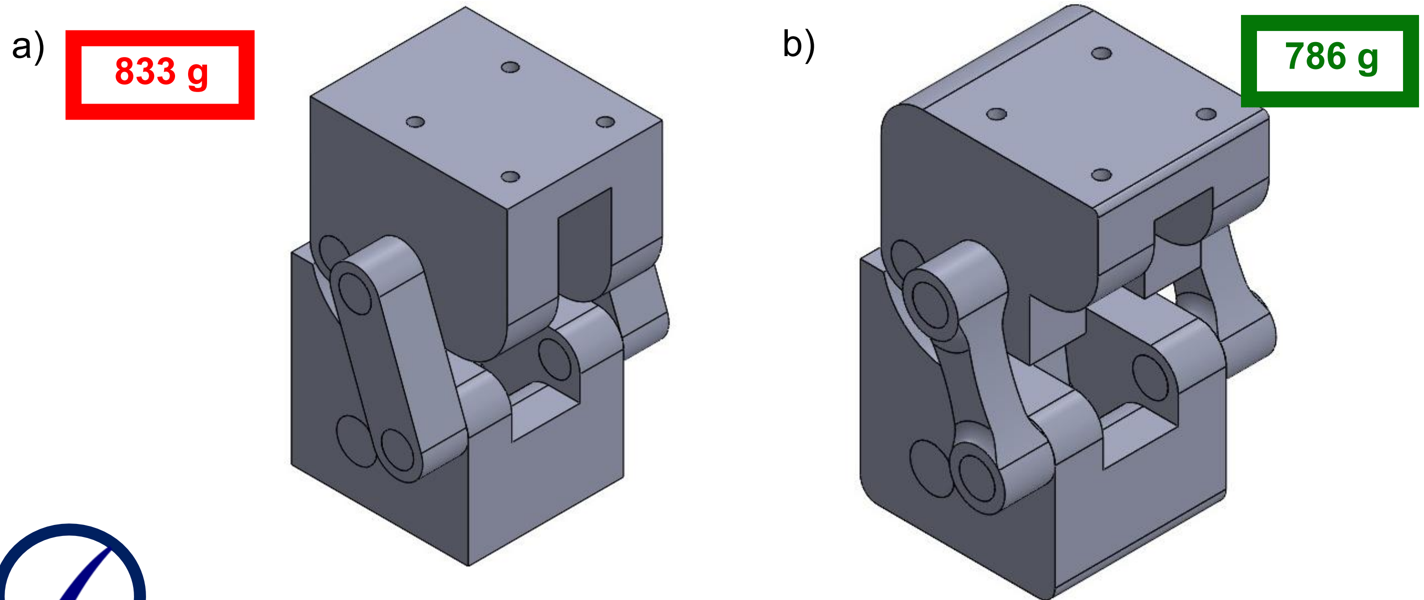


Figure 19: Comparison between a) Design 2 & b) Final Design

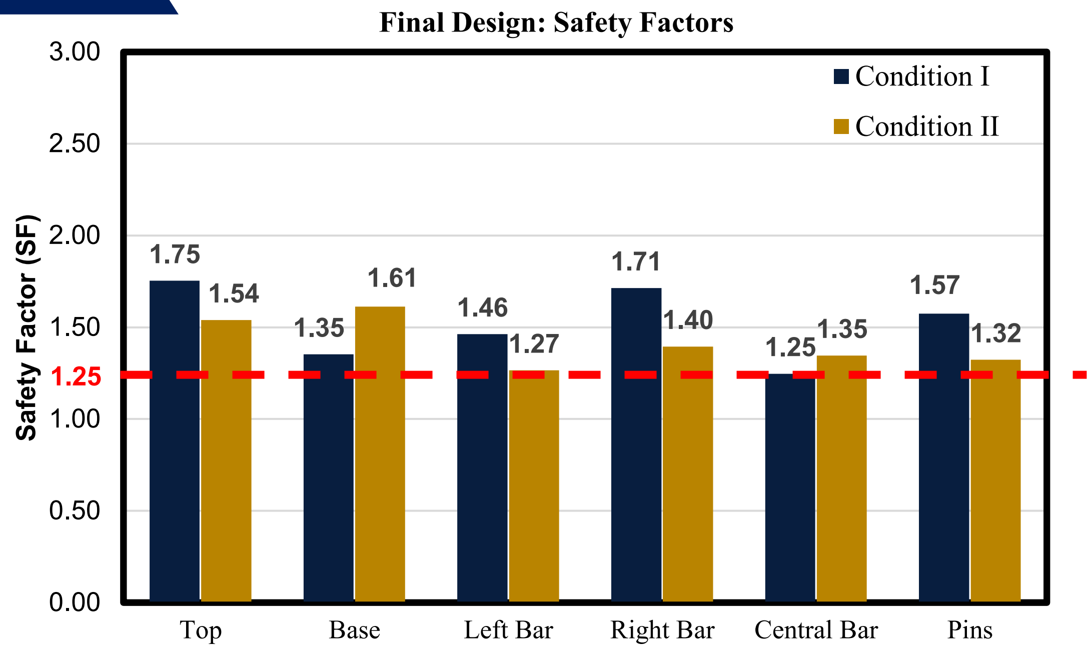


Figure 21: Safety Factors from Final Design

- ✓ Material removed through bottom, front, and rear fillet.
- ✓ Central and front top sections trimmed.
- ✓ Top pin divided and trimmed, lowering mass.
- ✓ Side bars with reduced width and thickness.

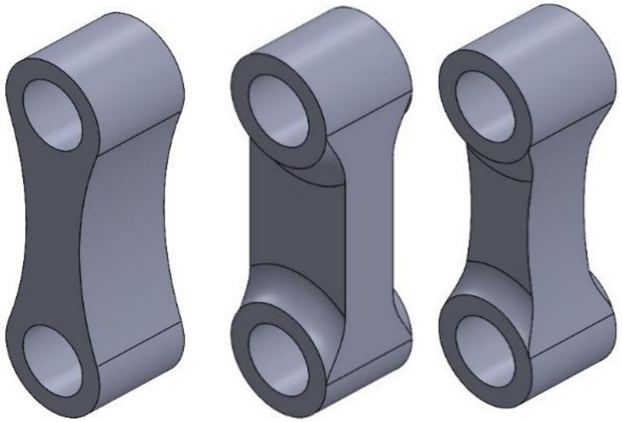


Figure 20: Side Bar Iterations

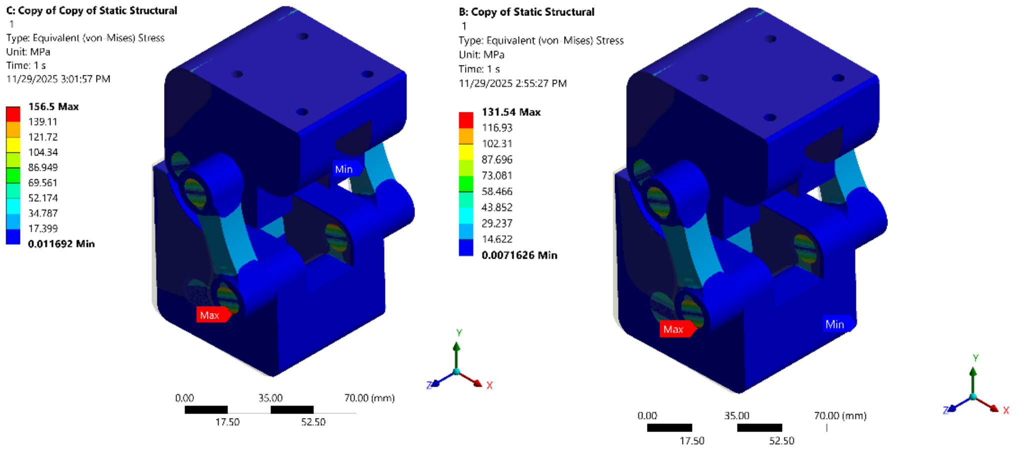
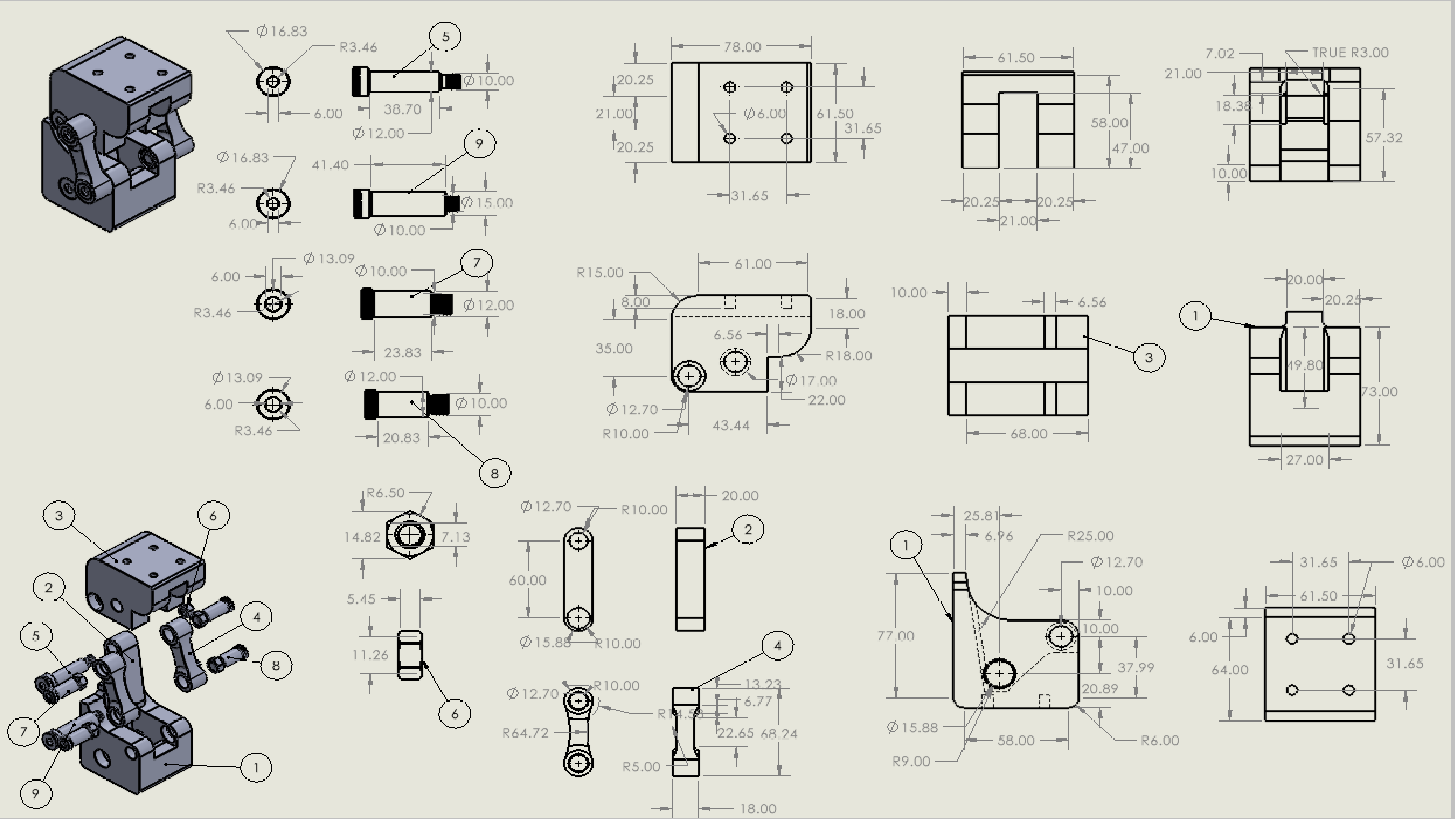


Figure 22: Stress Plots from Final Design


Ø16.83
R3.46
5
Ø10.00
6.00
38.70
Ø12.00
Ø16.83
R3.46
6.00
41.40
9
Ø15.00
Ø10.00
6.00
Ø13.09
R3.46
Ø10.00
7
Ø12.00
23.83
Ø13.09
6.00
R3.46
Ø12.00
Ø10.00
20.83
8
78.00
20.25
21.00
20.25
Ø6.00
61.50
31.65
31.65
61.50
58.00
47.00
20.25
20.25
21.00
7.02
TRUE R3.00
21.00
18.38
57.32
10.00
R15.00
61.00
8.00
18.00
35.00
6.56
R18.00
Ø17.00
22.00
Ø12.70
R10.00
43.44
10.00
6.56
3
68.00
20.00
20.25
1
49.80
73.00
27.00
3
6
2
4
5
8
7
1
9
R6.50
14.82
7.13
5.45
11.26
6
Ø12.70
R10.00
60.00
Ø15.88
R10.00
20.00
2
Ø12.70
R10.00
R64.72
R5.00
4
13.23
6.77
22.65
68.24
18.00
25.81
6.96
R25.00
1
Ø12.70
10.00
10.00
77.00
37.99
20.89
Ø15.88
58.00
R6.00
R9.00
31.65
Ø6.00
61.50
6.00
64.00
31.65

Manufacturing

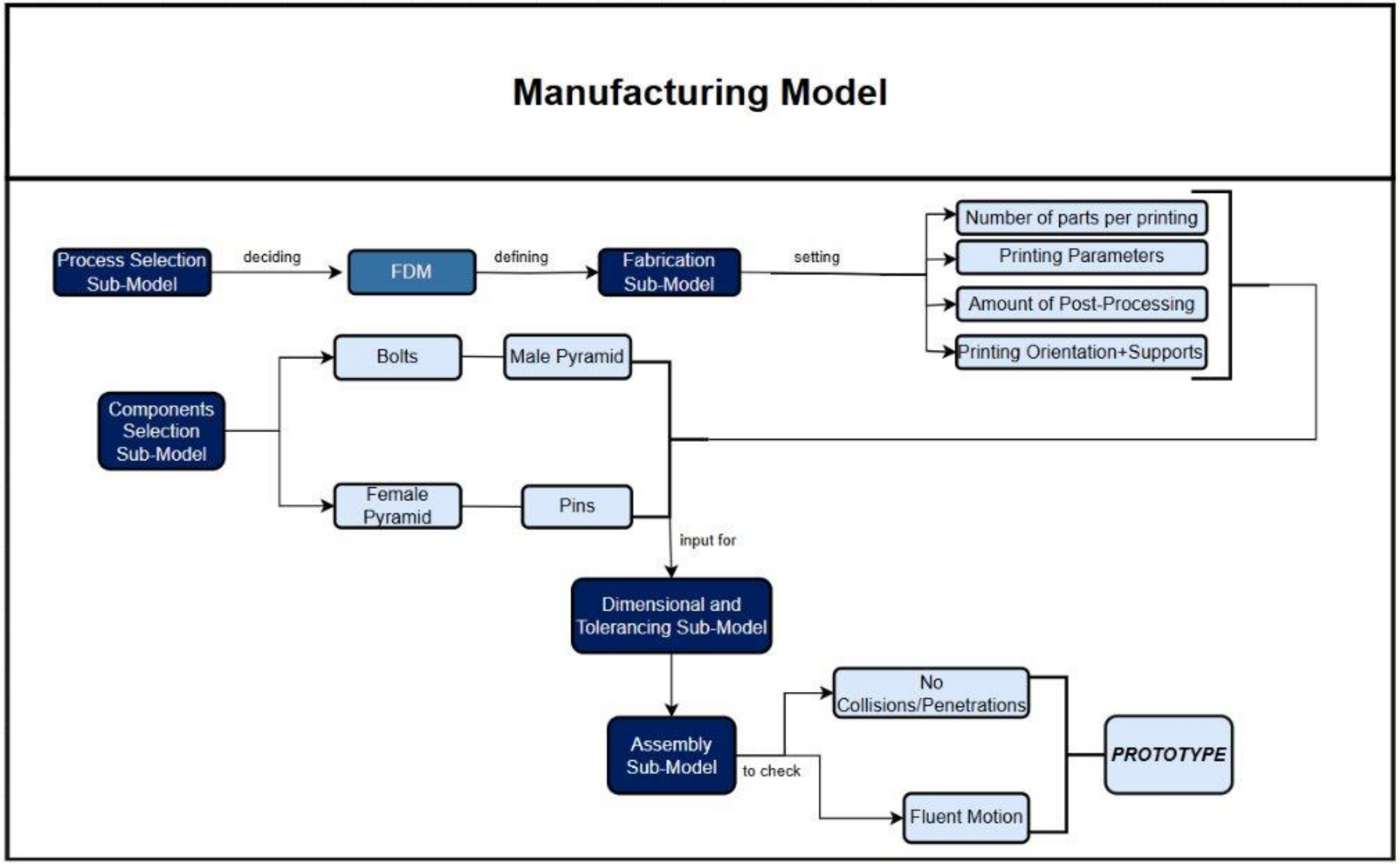


Figure 23: Prusa MK4

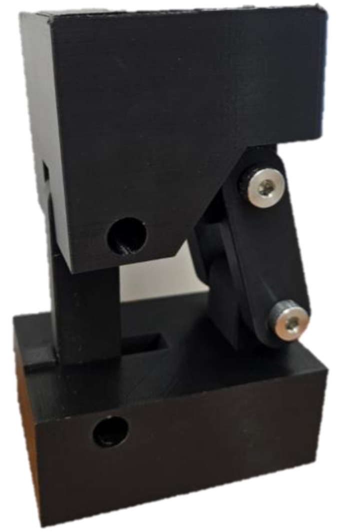


Figure 24:Prototype 1 Assembly

3D Printed Prototype

Figure 25: Side Bars and Central Bar

Figure 26: Top

Figure 27: Base

Assembly

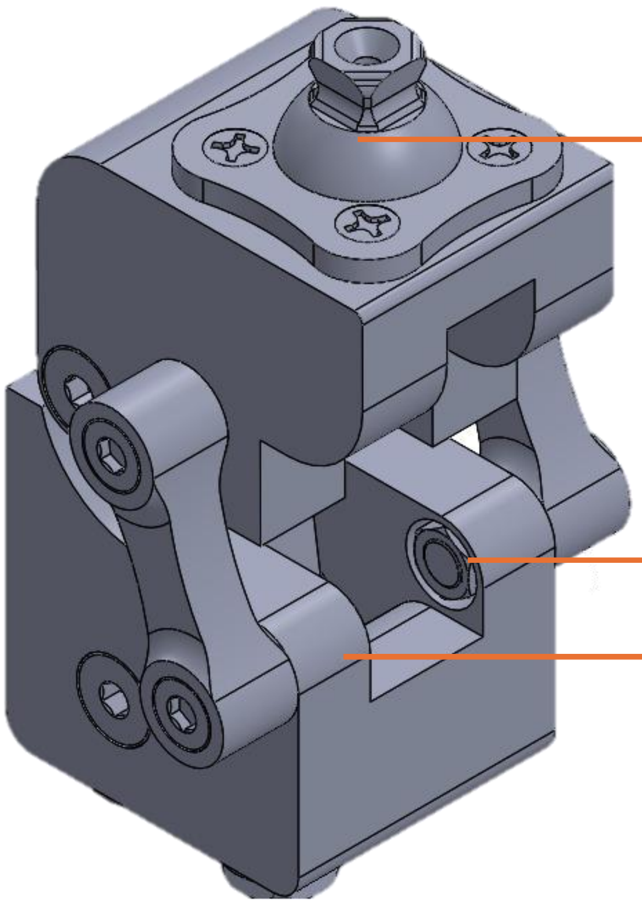


Figure 28: Isometric View of Final Design

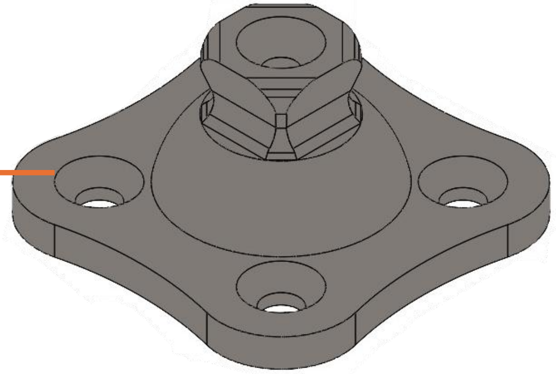


Figure 29: Pyramid Adapter

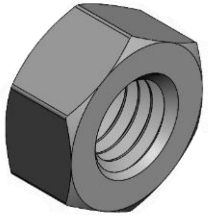


Figure 30: M8 Hex Nut

Figure 31: Shoulder Screw

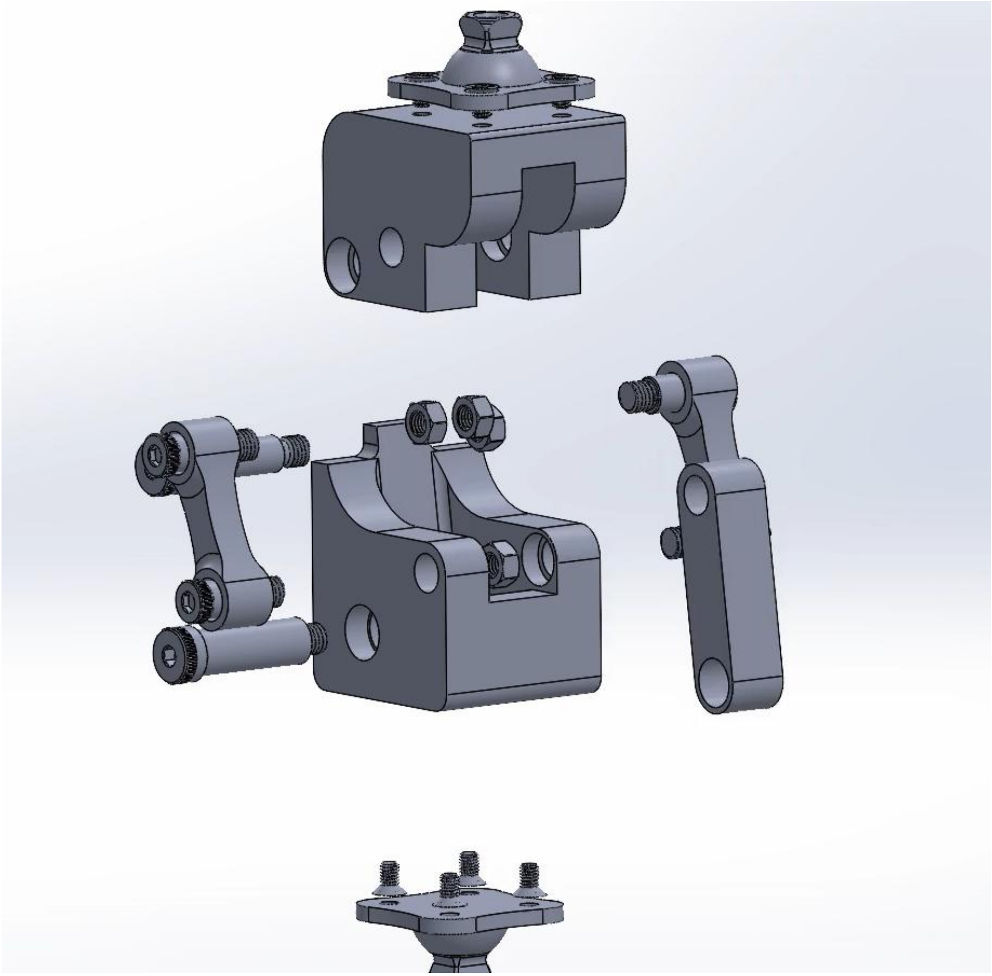


Figure 32: Assembly Process

Conclusions

Cost of $98.09 with adapters →	22.6% more expensive, but still acceptable if adapters are re-used
RMSE of 6.560 using DE →	39% reduction compared with GA
Lowest Safety Factor of 1.2472 →	Meets ISO 10328 for heel contact & push-off
93.37° maximum flexion motion →	Within 90°–100° sitting range
Joint weight equal to 786 g →	12.2% lighter (but +106 g more than Remotion)

THANK YOU.

Post-Processing

1

Epoxy Resin Coating:

- Coat parts with a layer of epoxy resin and let cure.
- Allows for a protective outer layer to form and increases the mechanical strength of the components.

2

Wet Sanding:

- Epoxy resin allows for the PLA to be primed for sanding by creating a thermal barrier.
- Wet sand with different grits used in progression, starting at 150 grit and finishing at 600 grit

3

UV Clear Top-Coat:

- Spray part with a UV-resistant acrylic clear coat to protect the epoxy surface from photodegradation,
- Prolonged UV exposure can cause epoxy resins to lose mechanical integrity over time