BiOM Prosthesis Adapter

Abdulla Ghayeb: Project Manager, Website Developer, CAD Lead
Ebrahim Hubail: Budget Liaison, Document Manager
Leah Liebelt: Client Contact, Carbon Fiber Lead, Document Editor

Background

Project Description

Goal: Design an adapter to span from an ankle prosthesis to the bent knee of an able-bodied person to allow research to be conducted on the BiOM without the need of an impaired subject.

Constraints: fit different sized users, lightweight, comfortable, durable, safe, cost effective, and quick attachment

Clients:
- Dr. Zachary Lerner
- Dr. Kiisa Nishikawa

Technical Advisers:
- Dr. Sarah Oman
- Amy Swartz

Figure 1: BiOM Ankle Prosthesis [1]

Requirements

Table 1: Customer Requirements

Requirement	Target Values
Light Weight (kg)	4
Comfortable	8/10 rating
Quick Attachment (sec)	60
Pylon Extension Range (cm)	12
Small/Large Calf Cuff Circumference (cm)	30 - 45
Small/Large Thigh Cuff Circumference (cm)	35 - 65
Durable	2 hours of continuous use
Affordable	$1000
Safe	FS of 3

The Design

Initial Design

Major Takeaways

- ➢ Adjustable pylon
- ➢ Adjustable leg straps
- ➢ Comfortable leg support
- ➢ Rigid bar for support

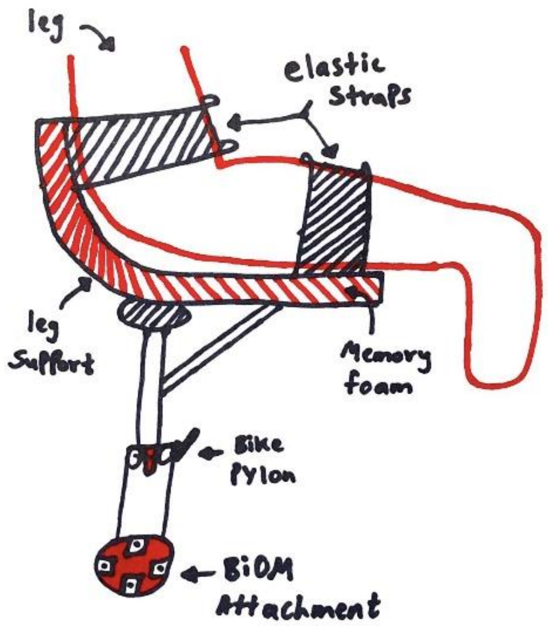

Figure 2: First Initial Design

Prototype

Major Takeaways

- Static design
  - No movement possible
- Two Adjustable leg cuffs
  - No support for the knee
- Adjustable pylon
- Two main subsystems
  - Leg support
  - Pylon

Figure 3: First Prototype

Design Changes

Allow rotation about the knee axis

- ➢ Use attachment subsystem
- ➢ Incorporate bearing
- ➢ Add spring system

Comfortability

- ➢ Knee Support

Robustness

- ➢ Change L-shaped design
- ➢ Use carbon fiber for L-shaped support, new attachment subsystem, and pylon

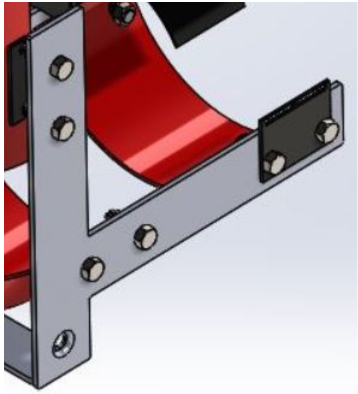

Figure 4: Prototype L-shaped Design

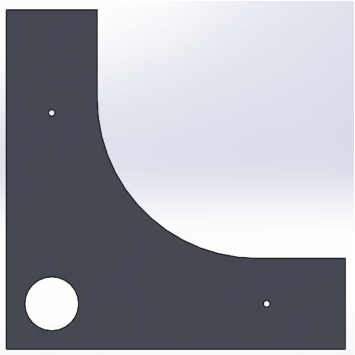

Figure 5: New L-shaped Design

Final Design

Major Takeaways

- ➢ Allows rotation of pylon about knee axis
- ➢ Pylon returns to extended position for new gait cycle
- ➢ Height adjustable pylon
- ➢ Width adjustable cuffs

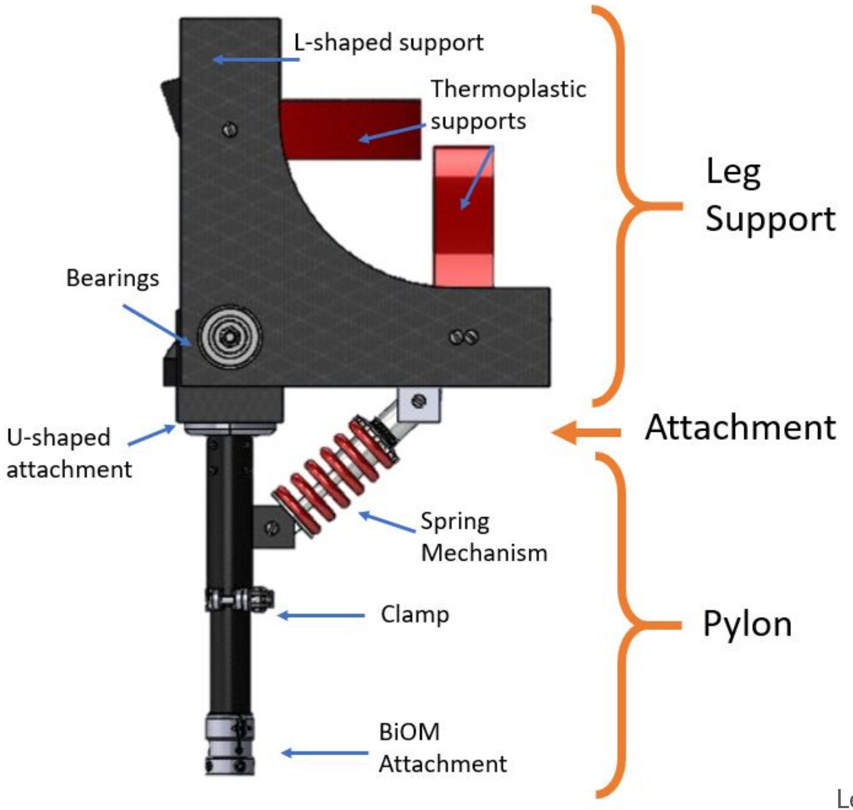

Figure 6: Final Design with Labeled Subsystems and Parts

Technical Analysis

Carbon Fiber U-Bar Attachment Analysis

<u>Carbon Fiber U-bar Analysis</u>: Determine the number of carbon fiber layers for U-bar attachment

- ➢ 9 layers for a factor of safety of 3 [2].
- ➢ Additional 3 layers to account for voids and delaminations.

Figure 7: Carbon Fiber U-bar support

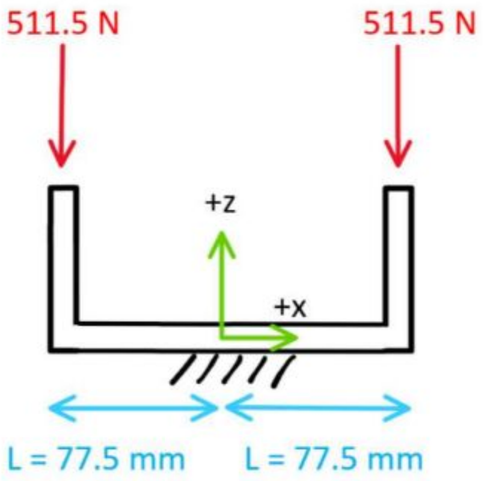

Figure 8: Simplified U-bar support

Bearing Analysis

Bearing Analysis: Determine type of bearing for knee axis rotation [3].

- ➢ Radial Force (C0)= 903 N
- ➢ Flange Ball Bearing
- ➢ Average bearing life = 4.033 L10 (about 1 year 10 months of constant use)

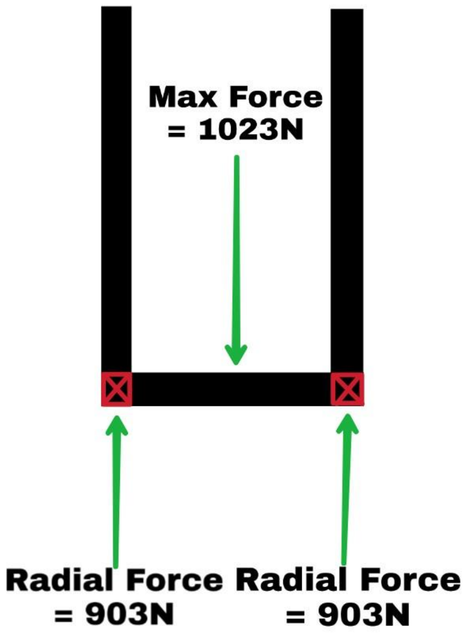

Figure 9: Bearing Placement

Manufacturing

Leg Support

Cuffs
- ➢ Heat and form thermoplastic
- ➢ Attach velcro straps

Fabricate L-shaped supports
- ➢ Cut shapes out of prepreg carbon fiber
- ➢ Stack 8 layers of carbon fiber sheet
- ➢ Vacuum bag and place in oven to cure
- ➢ Drill holes for bolts and bearings

Bearings
- ➢ Epoxy bearings in L-support

Figure 10: CAD Model of Leg Support

Attachment

U-Bar

- ➢ Cut prepreg carbon fiber to necessary shape
- ➢ Stack 12 layers into U shaped mold
- ➢ Cure in oven
- ➢ Drill 4 holes for attachment and 2 holes for the shoulder bolts

Pylon Attachment

- ➢ Attach pylon attachment to U-bar using 4 bolts and nuts

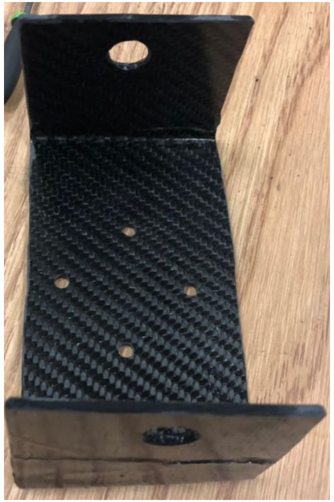

Figure 11: Carbon Fiber U-bar Support

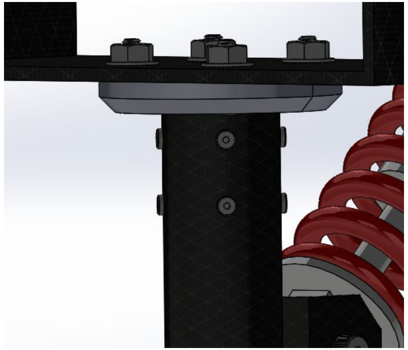

Figure 12: Attachment Subsystem

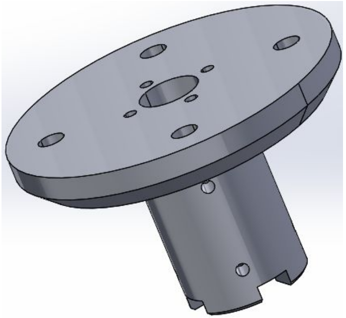

Figure 13: Pylon Attachment

Pylon

Pylon assembly

- ➢ Cut carbon fiber tubing
- ➢ Drill 8 holes in upper pylon
- ➢ Attach clamp
- ➢ Attach BiOM Attachment

Spring Mechanism

- ➢ Screw upper bracket to calf cuff
- ➢ Epoxy bracket to pylon
- ➢ Add spring into the hydraulic system

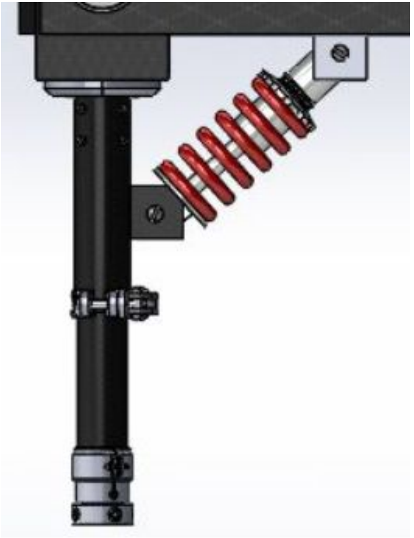

Figure 14: Pylon Subsystem with Spring Mechanism

Testing Procedures

Leg Support

Test 1:

1. Use 10 unbiased volunteers
2. Volunteers secured leg support to their leg without help
3. Volunteers put weight on bent knee resting on a rigid table
4. Rated comfort from 0 to 10, 10 being very comfortable, 0 being painful.
5. Device must have an average of 8/10

Figure 15: Comfort Test

Leg Support Continued...

Test 2:

1. Use same 10 volunteers to put the system on their leg
2. Determine the average time of attachment and adjustment

Test 3:

1. Measure maximum and minimum circumference of the calf and thigh cuffs
2. Cuffs must have 30 cm - 45 cm and 35 cm - 65 cm circumference ranges, respectively

Attachment

1. Attach U-bar to pylon without the leg support
2. Apply downward force to sides until U-bar breaks
3. Calculate actual factor of safety of the component

Note: U-Bar did not break during testing under applied load.

Figure 16: Attachment Testing Set-Up

Pylon

Test 1:
Measure maximum and minimum height of the pylon

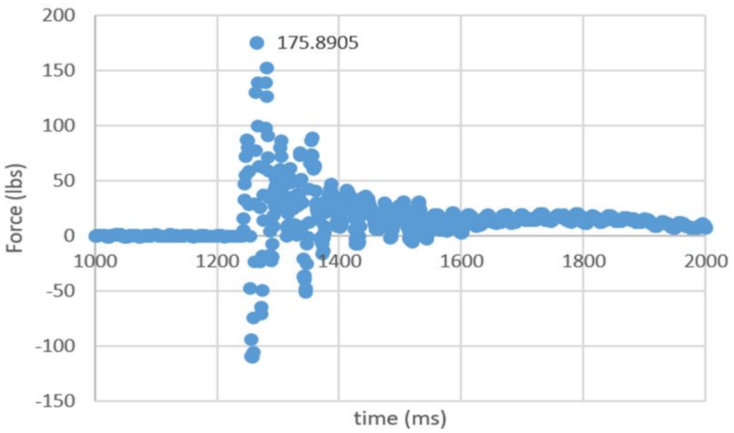

Figure 17: Pylon Slip Test

Test 2:

1. Stand pylon upright in extended position over a force sensor
2. Extend pylon to 2 inches above side-by-side tables
3. Apply force over top of pylon until pylon buckles/clamp slips to determine factor of safety.

System

Test 1: Weigh entire system to determine if system is under 4 kg

Test 2: Use bill of materials to determine if system is less than $1000.

Test 3: Use system continuously for 2 hours to determine durability.

Conclusion

Summary

Table 2: Results of Testing Procedures

Requirement	Target Values	Results
Light Weight (kg)	4	1.7
Comfortable	8/10 rating	8.3/10 rating
Quick Attachment (sec)	60	19.11
Pylon Extension Range (cm)	12	13
Small/Large Calf Cuff Circumference (cm)	30 - 45	27 - 41.5/41 - 46
Small/Large Thigh Cuff Circumference (cm)	35 - 65	30 - 42.5/42 - 68
Durable	2 hours of continuous use	TBD summer 2019
Affordable	$1000	$313.05
Safe	FS of 3	Critical FS of 3.2

Summary

- Need 2 sizes of leg support cuffs
- Minor slipping in the pylon with forces over 175 pounds, not a critical system failure
- Durability test to be completed in May 2019
- System compatible for heights of 5’ to 6’ 2” tall
- Entire system is affordable and lightweight
- Attachment time of about 20 seconds
- Comfort rating of 8.3/10

Future Work

- Complete durability test during the summer of 2019
- Construct a new leg support for smaller users
- Implement a torque sensor to knee joint axis
- Create knee actuation using motors or torque springs at knee joint to replace spring system

Thanks To...

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Dr. Ernesto Penado

Dr. John Tester

Dr. Constantin Ciocanel

NAU Biomechatronics Lab

W.L. Gore and Associates

Hanger Clinic

Copper State Bolt & Nuts

Single Track Bicycle Shop

References

[1] A. Ghayeb, E. Hubail, and L. Liebelt, *BiOM Ankle Prosthesis*. 2018.

[2] R. F. Gibson, *Principles of Composite Material Mechanics*, CRC Press 4th ed, 2016.

[3] Shigley's Mechanical Engineering Design, 9th or 10th Eds., R.G. Budynas & J.K. Nisbett, McGraw- Hill, 9th Edition 2011

[4] Liu, J., Ouyang, H., Peng, J., Zhang, C., Zhou, P., Ma, L., & Zhu, M. (2016). Experimental and numerical studies of bolted joints subjected to axial excitation.

Questions?

Appendix A: Budget

Budget

Sponsored by: W. L. GORE

Budget: $2,000

Balance: $65.16

Final Cost of Device: $313.05

Table A1: Breakdown of Cost

	Price of Parts
Pylon	$210.44
Attachment	$96.57
Leg Support	$379.10
Future work	$675
Tools	$80.81
Tax & Shipping	$492.92
Total Spent	**$1,934.84**

Appendix B: Technical Analysis

Carbon Fiber U-Bar Attachment Analysis

<u>**Carbon Fiber U-bar Analysis**</u>: Determine how many carbon fiber layers are needed in the U-bar attachment layup using a composites analysis.

- ➢ Utilized the Promal Composites Program to solve for maximum allowed stress [2]
- ➢ $$\sigma_{allow} = \frac{F \times L \times \left(l \times \frac{t_{1-ply}}{2}\right)}{w \times \left(\frac{\left(l \times t_{1-ply}\right)^{3}}{12}\right)}$$
  solve for l to determine carbon fiber layers
- ➢ A minimum of 9 layers are needed for a factor of safety of 3 [2].
- ➢ Additional 3 layers were used to account for voids and delaminations within the component.

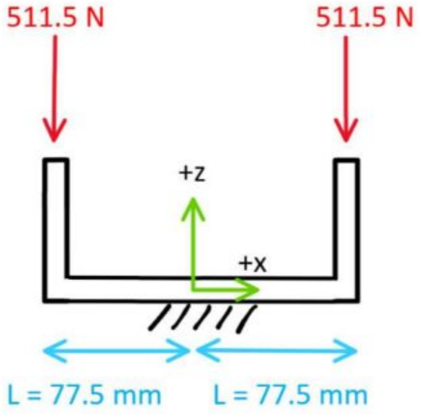


Figure B1: Simplified U-bar support

Moving Forward: Bearing Analysis

<u>Bearing Analysis:</u> Determine radial force acting on bearing location to determine the type of bearing needed [3].

- ➢ Ball Bearing

$$C_0 = F_R = F_D \left(\frac{L_D}{L_R}\right)^{\frac{1}{a}} = F_D \left(\frac{\mathcal{L}_D n_D 60}{\mathcal{L}_R n_R 60}\right)^{\frac{1}{a}}$$

- ➢ Radial Force (C0)= 903 N
- ➢ Average bearing life = 4.033 L10 (about 1 year 10 months of constant use)

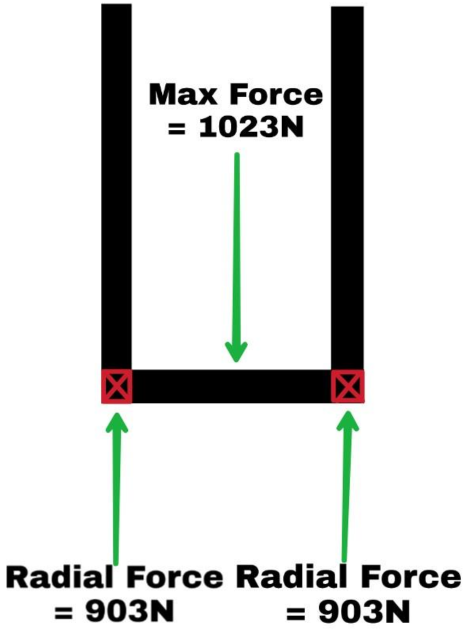


Figure B2: Bearing Placement

Moving Forward: Shoulder Bolt Analysis

Shoulder Bolt Analysis: Determine the right shoulder bolt that attaches to the bearing to the leg support [4].

- Force: 511.5 N
- 1/2" Shoulder Diameter
- Minimum Shear Strength: 84,000 psi
- Tensile Strength: 140,000 psi

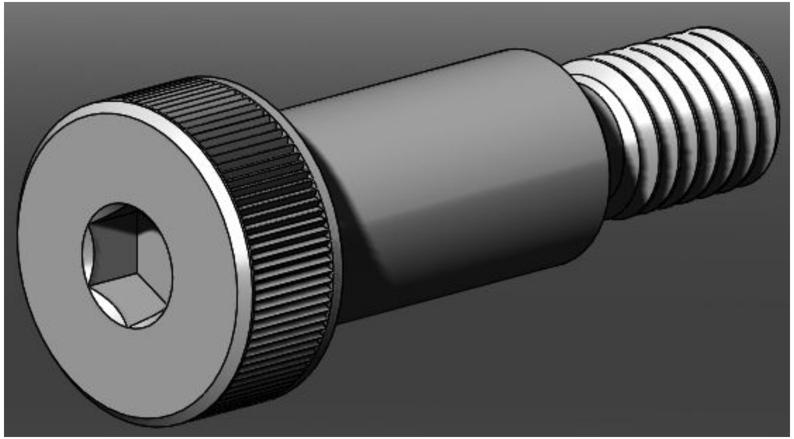


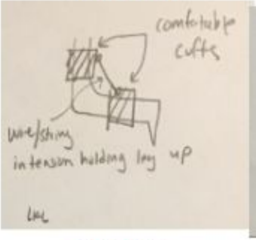
Figure B3: Shoulder Bolt

Appendix C: Initial Concepts

Pugh Chart (Leg Support)

Table C1.1: Leg Support Pugh Chart

DATUM (1)



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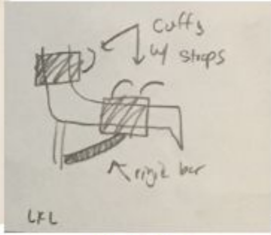

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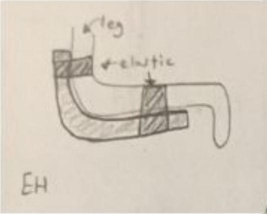

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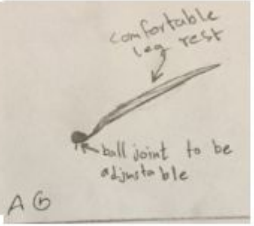

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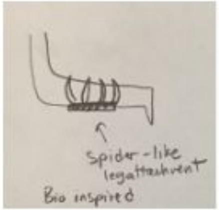
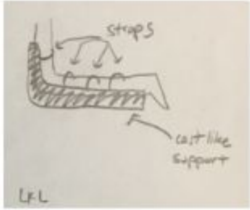
Criteria	DATUM	Rigid Bar	El Hefe	Ball/Joint	The Cloud
Safety	0	0	0	-1	-1
Durable	0	1	1	-1	-1
Light Weight	0	0	-1	1	1
Adjustable	0	0	0	0	0
Quick Attachment	0	1	1	0	0
Comfortable	0	0	1	1	1
Number better: S+	+0	+2	+3	+2	+2
Number worse: S-	0	0	-1	-2	-2
Number same: S0	6	4	2	2	2

Pugh Chart (Leg Support) continued

Table C1.2: Leg Support Pugh Chart

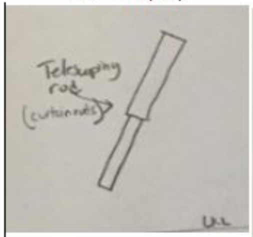


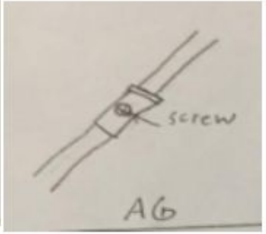


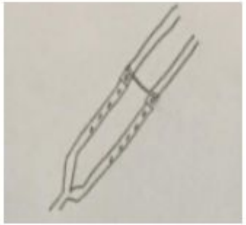
	6	7	8	9
Criteria	The Spider	Straps	The Cast	Bowl of Sand
Safety	-1	0	1	-1
Durable	0	0	1	0
Light Weight	-1	1	-1	-1
Adjustable	1	1	0	-1
Quick Attachment	0	0	0	-1
Comfortable	0	0	0	1
Number better: S+	+1	+2	+2	+1
Number worse: S-	-2	0	-1	-4
Number same: S0	3	4	3	1

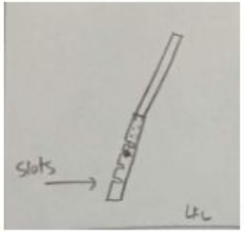
Pugh Chart (Pylon)

Table C2.1: Pylon Pugh Chart









	DATUM(10)	11	12	13	14
Criteria	Telescoping rod pylon	Screw pylon	Crutches pylon	Crutches pylon2	Slots pylon
Safety	0	1	1	1	0
Durable	0	1	1	0	1
Light Weight	0	0	-1	0	0
Adjustable	0	0	-1	-1	-1
Quick Attachment	0	-1	-1	-1	0
Stable	0	1	1	0	0
Quick Adjustment	0	0	0	0	1
Number better: S+	+0	+3	+3	+1	+2
Number worse: S-	0	-1	-3	-2	-1
Number same: S0	7	3	1	4	4

Pugh Chart (Pylon) continued

Table C2.2: Pylon Pugh Chart (cont.)

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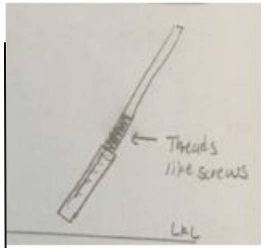

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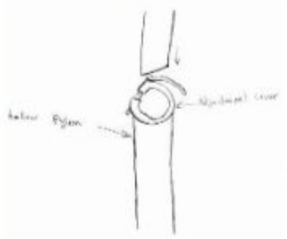

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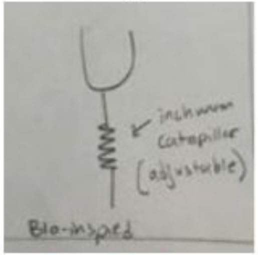
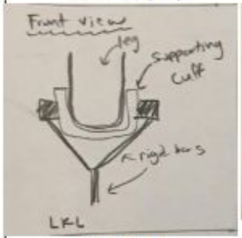


	15	16	17	18
Criteria	Thread pylon	Hiking pylon	Bike pylon	Catapiller pylon
Safety	-1	1	1	-1
Durable	0	0	1	0
Light Weight	0	1	1	0
Adjustable	1	1	1	0
Quick Attachment	0	0	0	1
Stable	-1	1	1	-1
Quick Adjustment	1	1	1	0
Number better: S+	+2	+5	+6	+1
Number worse: S-	-2	0	0	-2
Number same: S0	3	2	1	4

Pugh Chart (Attachment)

Table C3: Attachment Pugh Chart

DATUM(19)



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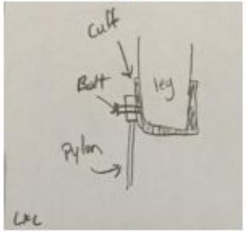

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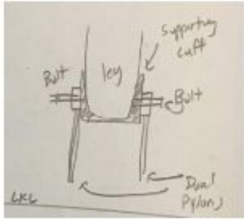

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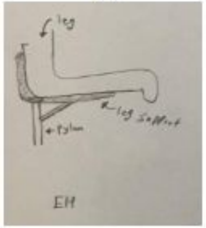

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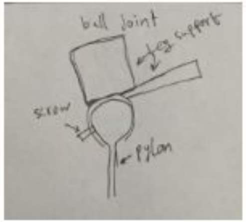

Criteria	DATUM	Under Knee	Parallel	Double up	Truss	Ball Joint
Safety	0	-1	0	1	1	0
Durable	0	0	0	1	1	0
Light Weight	0	1	1	-1	0	0
Quick attachment	0	-1	1	0	1	-1
Stable	0	-1	0	1	1	0
Number better: S+	+0	+1	+2	+3	+4	+0
Number worse: S-	0	-3	0	-1	0	-1
Number same: S0	5	1	3	1	1	4

Final Sketches

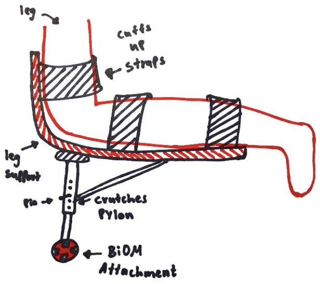

Figure C1: Final Sketch 1

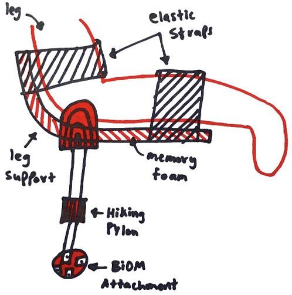

Figure C3: Final Sketch 4

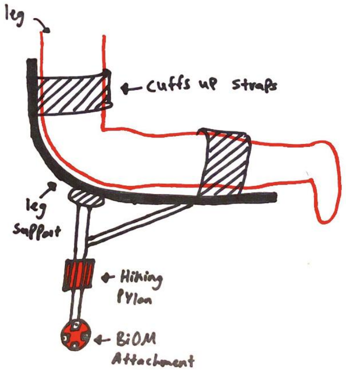

Figure C5: Final Sketch 5

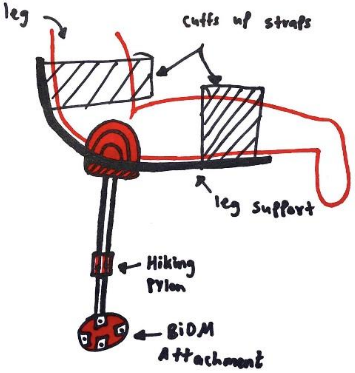

Figure C2: Final Sketch 2

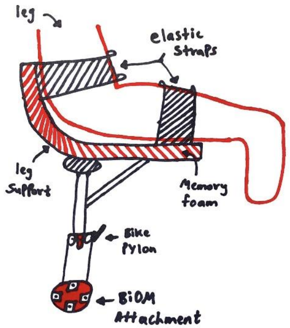

Figure C4: Final Sketch 3

Decision Matrix - Top Concepts

Table C4: Final Concepts Decision Matrix

SET 1		Final Sketch 1		Final Sketch 2		Final Sketch 3		Final Sketch 4		Final Sketch 5	
Criteria	Weight (%)	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Safety	17%	80	13.6	70	11.9	80	13.6	60	10.2	80	13.6
Durable	15%	85	12.75	75	11.25	90	13.5	70	10.5	75	11.25
Quick Attachment	10%	60	6	70	7	70	7	70	7	70	7
Lightweight	16%	30	4.8	50	8	40	6.4	70	11.2	70	11.2
Stable	13%	70	9.1	50	6.5	75	9.75	50	6.5	70	9.1
Adjustable	14%	90	12.6	75	10.5	80	11.2	80	11.2	75	10.5
Comfortable	15%	80	12	60	9	90	13.5	90	13.5	75	11.25
Total	100%		70.85		64.15		74.95		70.1		73.9