Team Cavatappi UGRAD Presentation

JAMES BENNETT, PATRICIA ANN LESTER, RYN SHUSTER

Contents

Project Description

- Continuation of Dr. Diego Higueras-Ruiz's Research on artificial soft robotic muscles
- Research conducted in Dr. Michael Shafer's Dynamic Active Systems Lab
- Tasked with:
  - Developing updated manufacturing process
  - Utilizing muscles to design functional end effector
  - Applying manufacturing process to scale down muscles

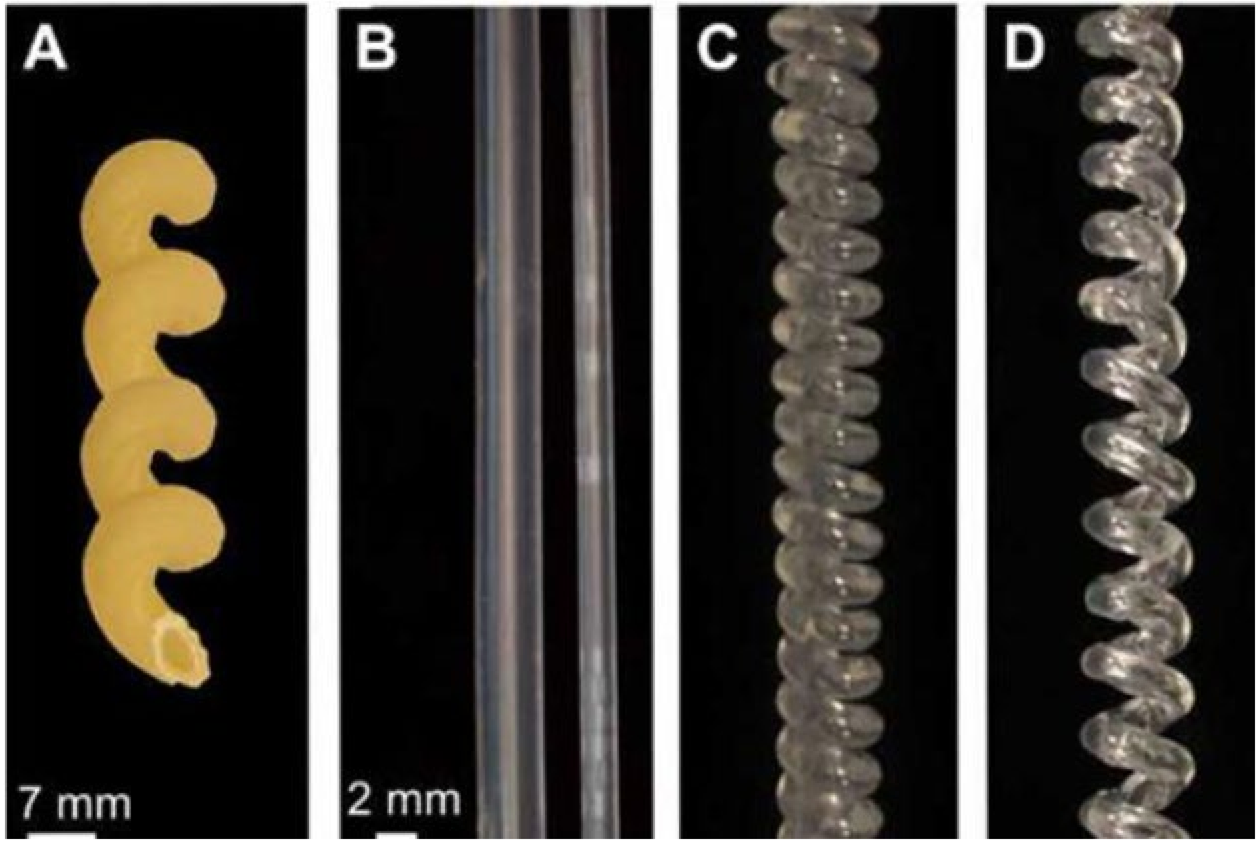


Figure 1: Cavatappi pasta vs. Cavatappi Muscle materials [1]

Project Background

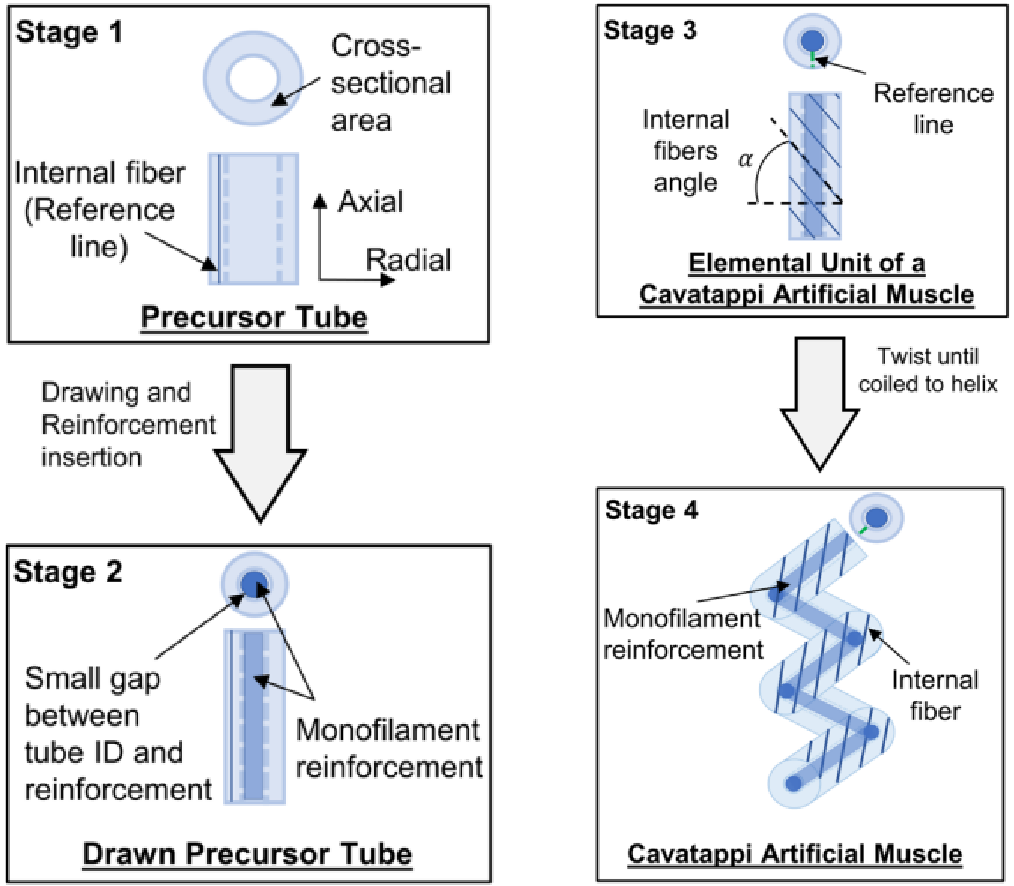


Figure 2: Manufacture process [1]

Customer Requirements

- Update muscle manufacture
- Scale down muscles
- Produce reliable muscles
- Develop End Effector/ Demo
- Safe to operate
- Budget: $200
- Utilize muscle bundles (parallel)
- Individual finger actuation
- Maximum “hand” size: 10 cm cube
- Reduce leaks

Engineering Requirements

- End effector size: V > 10 x 10 x 10 cm
- Muscle coil diameter: < 4.0 mm
- Cost: < $200.00 USD
- Safety factor: SF > 1
- Muscles per Bundle: N > 1
- Muscle Length (L)
- Manufacture system efficiency (%)
- Muscle mechanical efficiency: > 20% [1]

Initial System: Manufacturing

Figure 3: Initial Manufacturing Setup – Clamps (left), Heating (middle), Coiling (right)

Decision Making: Manufacturing

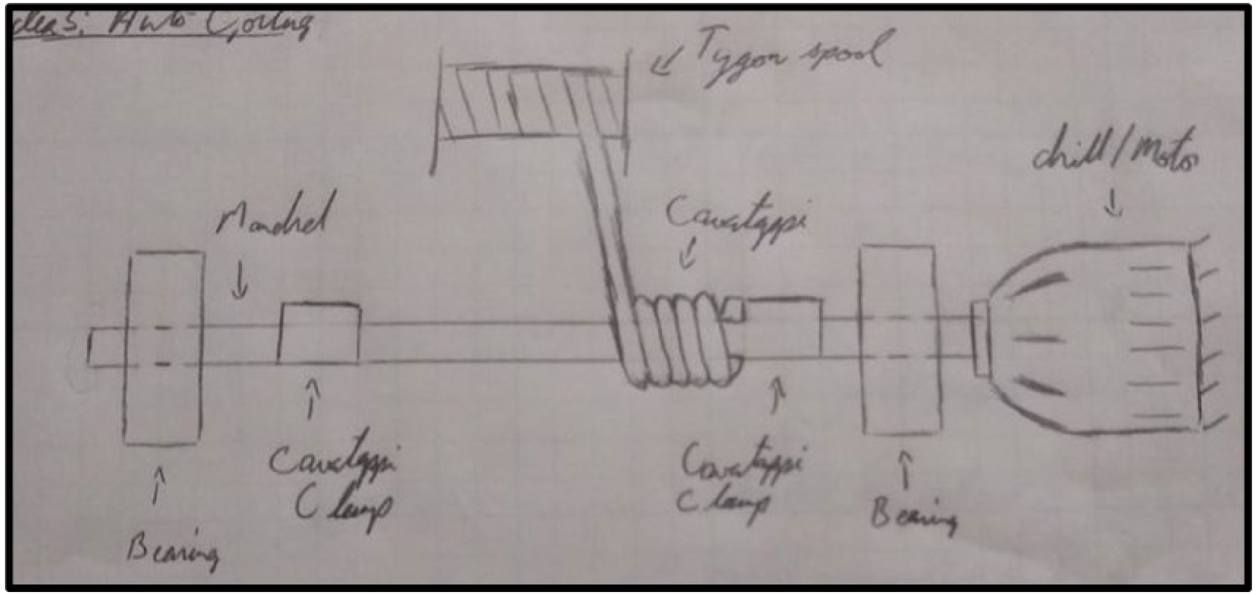


Figure 4: Spooling Method

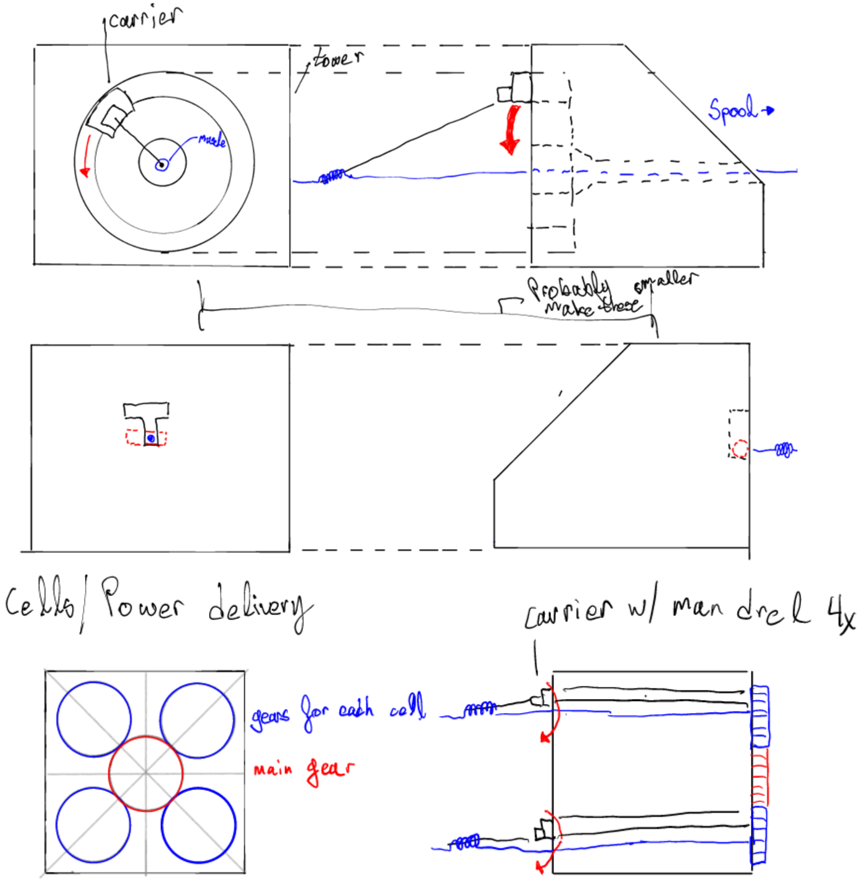


Figure 5: Carrier Method

Decision Making: Manufacturing Design

Main Criteria

- Muscle Scalability
- System Reliability
- Muscle Quality

Deciding Factors

- System Reliability
- Ease of Construction

Decision Matrix: Muscle Production					
		Carrier Method		Spooling Method	
Criteria	Weight	Percentage Met	Weighted Score	Percentage Met	Weighted Score
A-Scalability of Muscle Length	10.00	80%	8.00	80%	8.00
B-Reliabity of system	30.00	70%	21.00	85%	25.50
C-Flexibility of system	5.00	80%	4.00	85%	4.25
D-Quality of Muscle	25.00	90%	22.50	90%	22.50
E-Simplicity of Design	15.00	60%	9.00	85%	12.75
F-Ease of Construction	15.00	55%	8.25	85%	12.75
Total Points	**100**		**72.75**		**85.75**
Relative Ranking	1st/2nd	2nd		1st	

Table 1: Decision Matrix

Design Solution: Manufacturing Final System: Spooling Method

- Pros
  - Mandrel/muscle are parallel
  - Simpler twisting and coiling method
  - Easy to operate
  - Few failures (86.7% success rate)
  - Cheap (3-D Printed)
- Cons
  - Clamps must be baked with muscles
  - Limited muscle length
  - Muscles are individually made

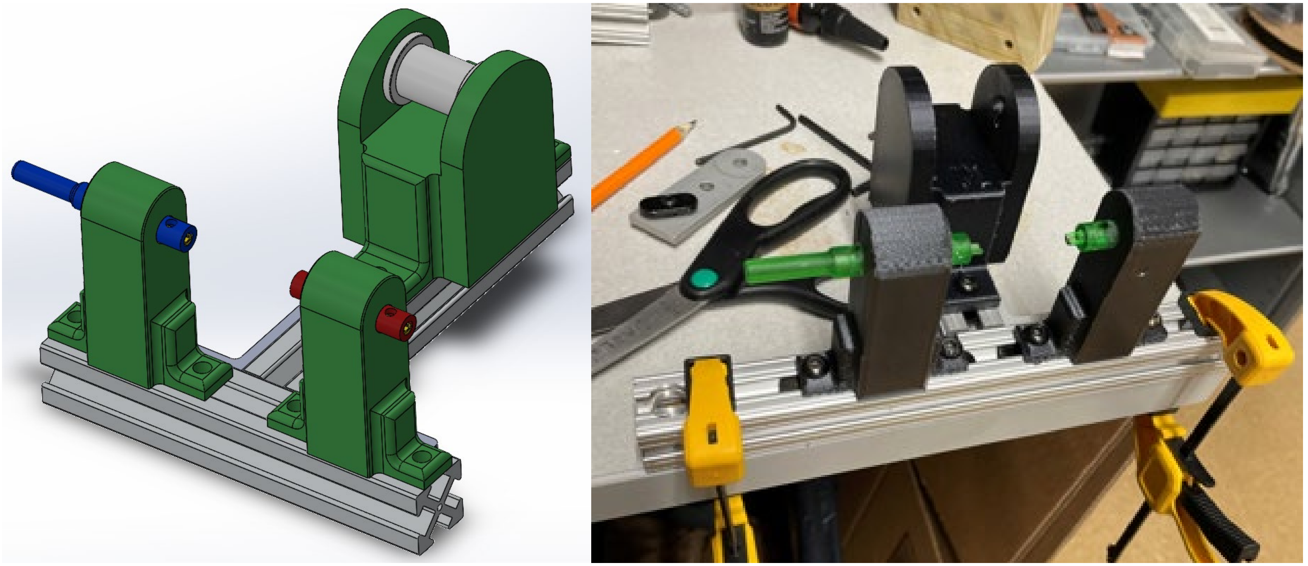


Figure 6: Spooling Method CAD (left) and Final System (right)

Testing: Material

Tygon Material types:

- Large: 3/16” OD, 1/16” ID
- Medium: 3/32” OD, 1/32” ID
- Small: 1/32” OD, 1/64” ID

Small/Medium Material

- Uneven heating (burns)
- Difficult to mount
- Would not pressurize
- Seam along tubing caused failures

Large Material

- Pressurized and mounted
- Even heating

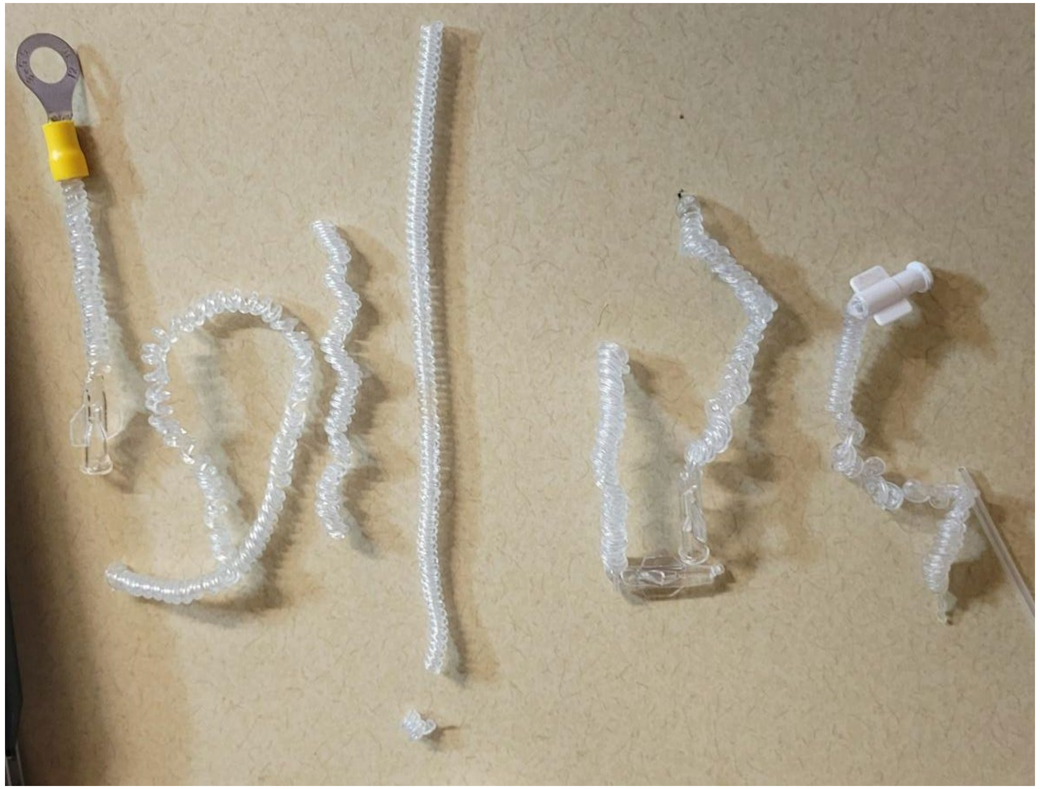


Figure 7: Failed Muscles

Change in Scope: Muscle Size Scalability

Problems with Muscle Size Scalability

- Small material was too delicate to scale
- Medium material drew incorrectly
- Burned often
- drawing and coiling was inconsistent

Client (Dr. Shafer) deemed Scalability low priority

- Focus on larger muscles
- Focus on muscles in parallel

Design Solution: Manufacturing Final System: Sous Vide

Figure 8: Anova “sous vide” heater and circulator

Figure 9: Vacuum sealed muscle

Testing: Heating

- Iterative heating tests
  - Max Working Temp: 165 °F [2]
  - Temps: 140 – 170 °F, 10 ° step size
  - Time: 5 min step size
- 3 Sections
  - Undrawn/untwisted/uncoiled
  - Undrawn/untwisted/coiled
  - 2x drawn/twisted/coiled

Temperature (F	Observed Time (min)	Length (cm)	Monofilament	Next steps	Notes
170	5	5	Present	No useful changes	
170	10	5	Present	Proceed to undrawn/coiled test	
170	15	5	Present	No useful changes	Too brittle, lower temperature
160	5	5	Present	No useful changes	
160	10	5	Present	No useful changes	
160	15	5	Present	No useful changes	
160	20	5	Present	No useful changes	
160	25	5	Present	Proceed to undrawn/coiled test	Lower temperature correlates to higher cook time
150	20	5	Present	No useful changes	
150	25	5	Present	No useful changes	
150	30	5	Present	No useful changes	
150	35	5	Present	Proceed to undrawn/coiled test	
140	30	5	Present	No useful changes	
140	35	5	Present	No useful changes	
140	40	5	Present	No useful changes	
140	45	5	Present	Proceed to undrawn/coiled test	Testing time becoming inefficient, omit 130 and 120 tests

Table 2: Testing Parameters

Manifold Development: Initial Design steps

Manifold: A way to gather and distribute hydraulic energy in a system.

Criteria:

- 3D Printed
- Scalable (2-6 muscles per bundle)
- Can be hooked up to “Luer” hardware
- Minimized overall size and interior chamber

Markforged Mk II Printer

- Durable material
- Quick
- Accurate

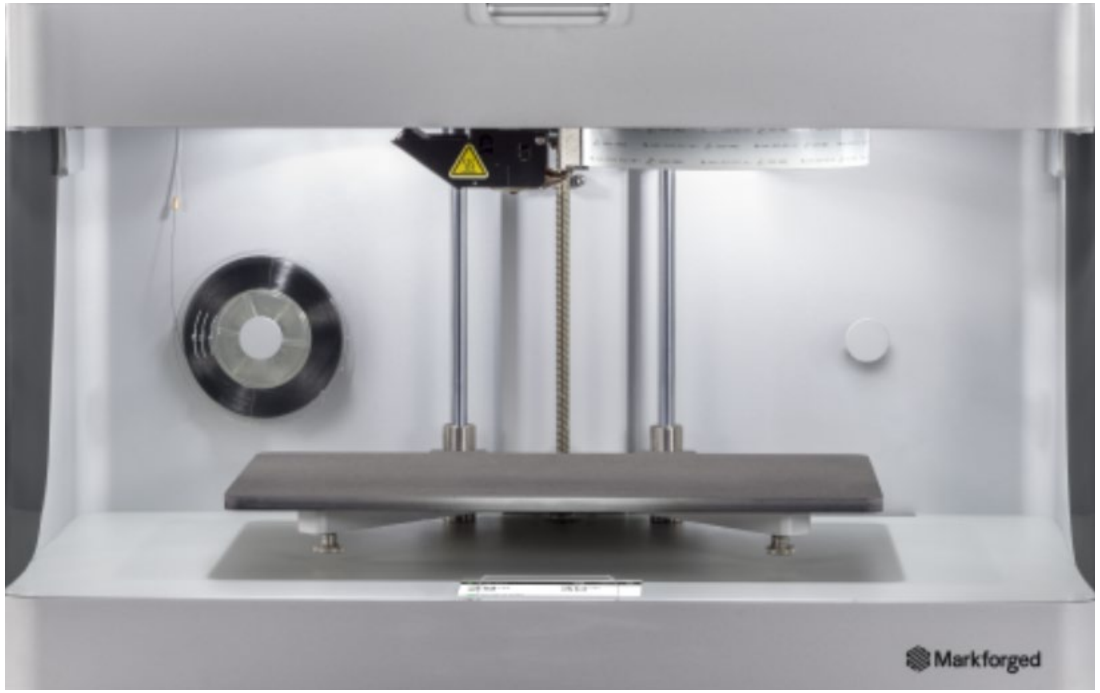
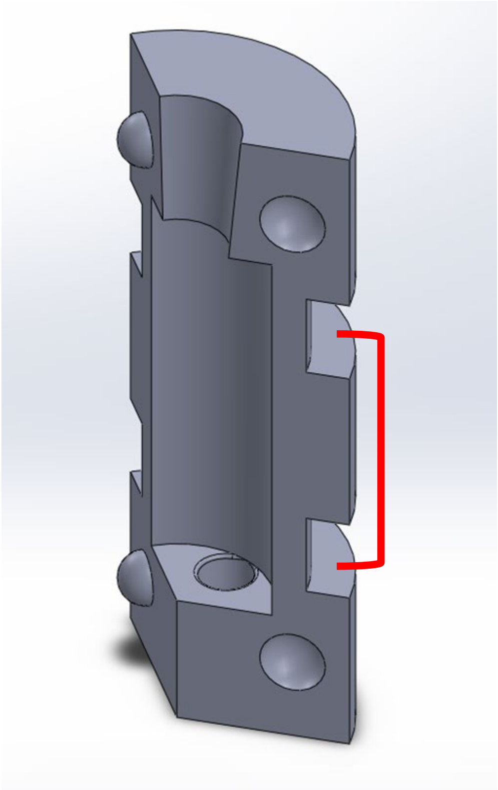


Figure 10: Markforged Mk II

Manifold Development: Initial Design

Segmented Manifold
- Each segment would contain 1 muscle.
- 3 glued together
- Thread impregnated with resin to help seal.

First Single Piece Design
- No support material from print inside fluid chamber
- Much faster manufacturing



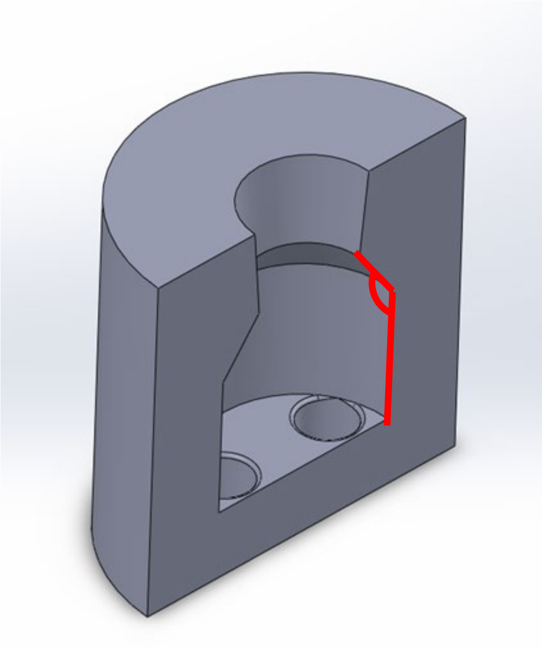


Figure 11: Segment Manifold (Left) Single Piece Manifold (Right)

Final Manifold Design

- Single component
- Easily scales for multiple muscles
- Designed to attach to already existing clips and mounting system

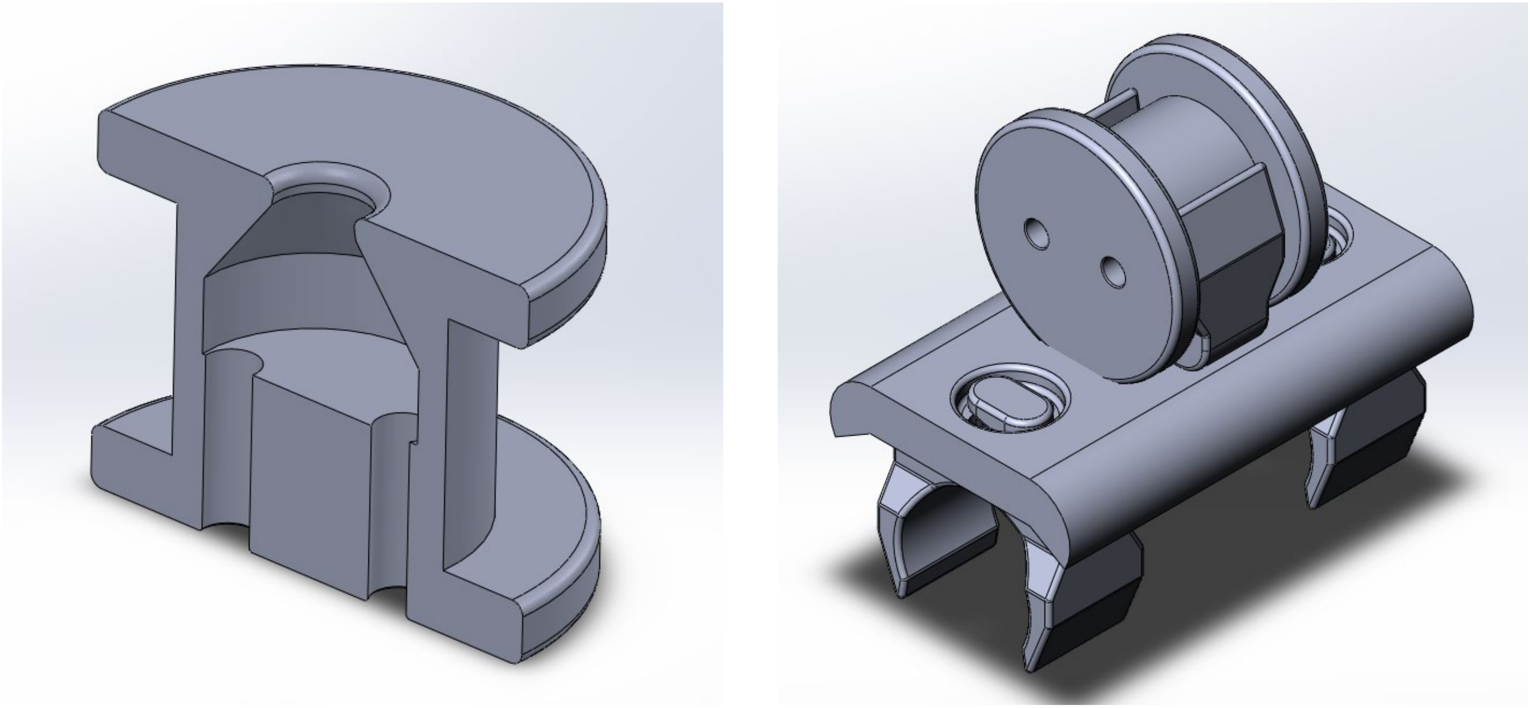


Figure 12: Final Manifold Cut-away and Mounted Manifold

Testing: Manifolds

-First Design:

- Too Difficult to reliably seal

-Second Design:

- Failed due to lack of muscle actuation
- Too small to effectively mount
- Successfully pressurized as single piece print

-Third Design:

- Large muscle material
- Muscles mounted in pairs to minimize twisting.

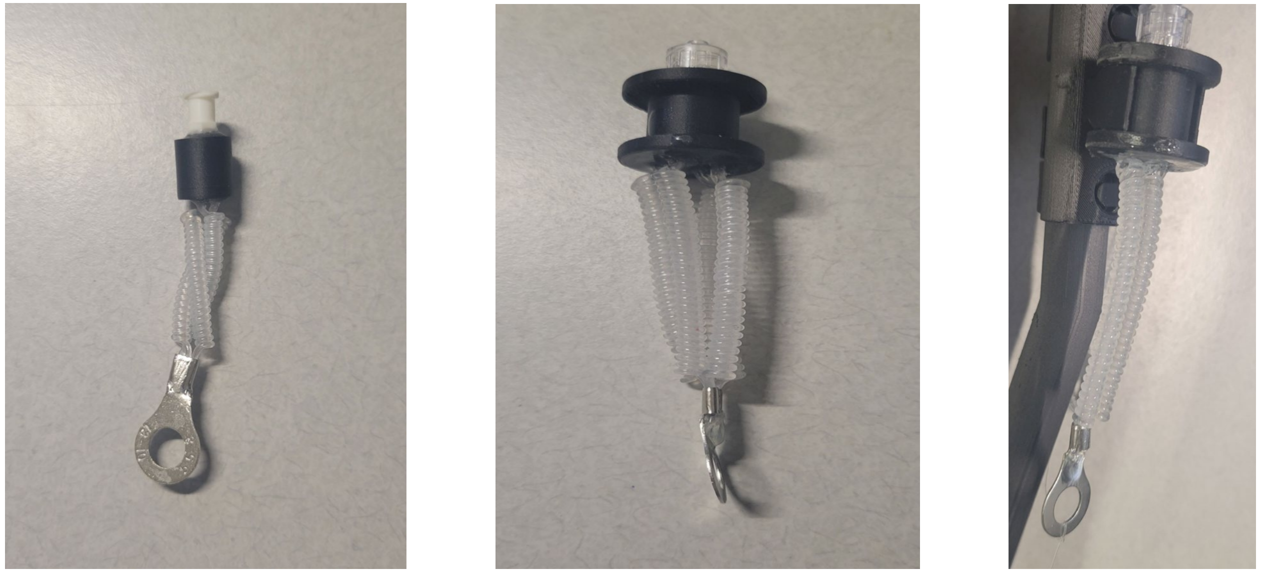


Figure 13: Second, 4 Muscle 3rd Gen, Final 2 Muscle 3rd Gen

Working Muscle

- Working Muscle Bundle
  - 32 active coils, 4.0 cm length
  - 2x muscles of 3x draw length
  - 0.5 kg weight
  - ~ 150 psi (1.03*10^6 Pa)
  - ~ 0.4 mL fluid (4.0*10^-7 m^3)
  - ~ 3.0 cm deflection (0.03 m)
- Efficiency
  - $eff = {}^{W_{out}}/_{W_{in}} = {}^{mgh}/_{P*V} = 0.356$
  - 35.6% efficiency (21.0%) [1]

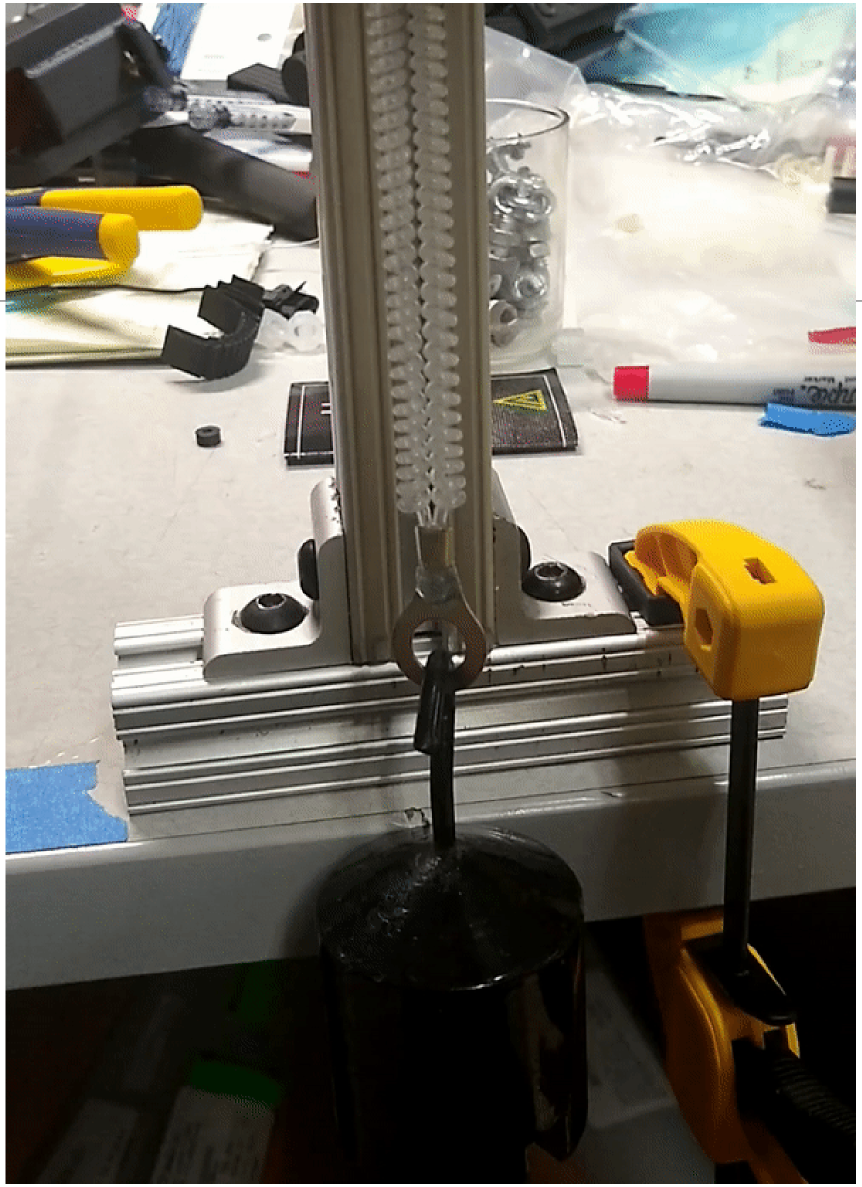


Figure 14: Actuating Bundle

Decision Making: End Effector

Design considerations:

- Ultimate task was going to be small in nature.
- Bio-mimicry requested by customer
- Modularity requested by customer
- Access to high strength and accuracy 3D printer for final design

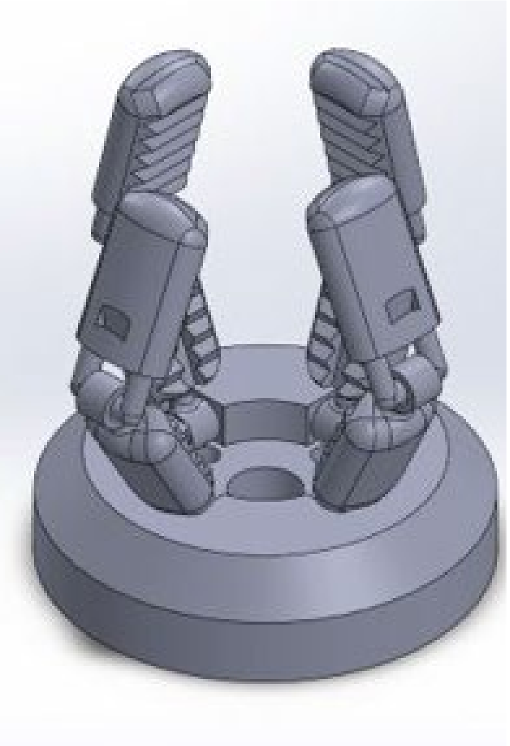


Figure 9: Initial End-Effector Concept

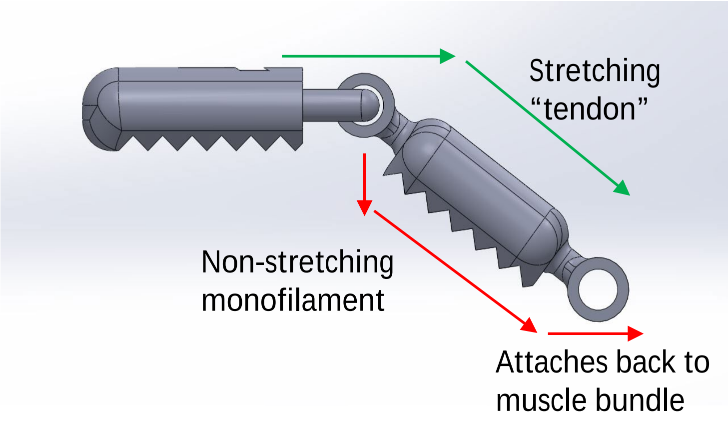


Figure 10: Initial "Finger" Design

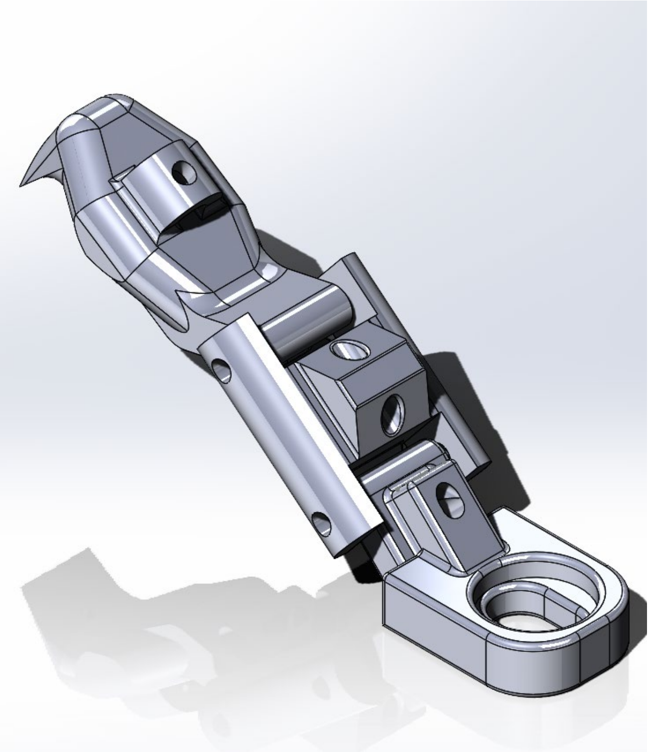
Design Solution: End Effector
Final System: Bird's Claw

Modular:

- Center hub can accept a variety of "fingers"
- Center Hub is easily removable

Fingers easily assembled

- Elastic and monofilament can be reversed to make the system squeeze to open.
- Satisfies customers bio-mimetic design request
- Each finger can be individually actuated.



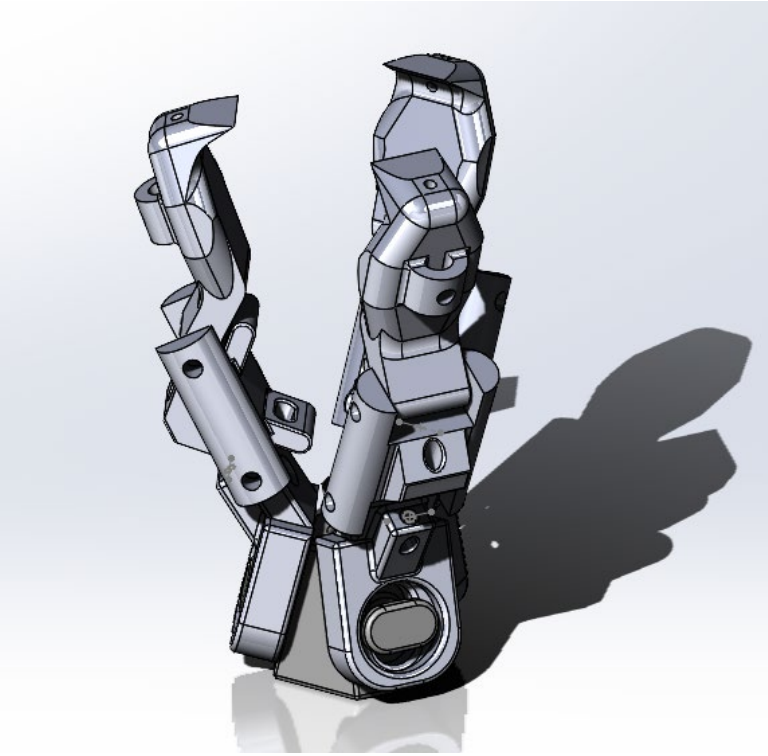
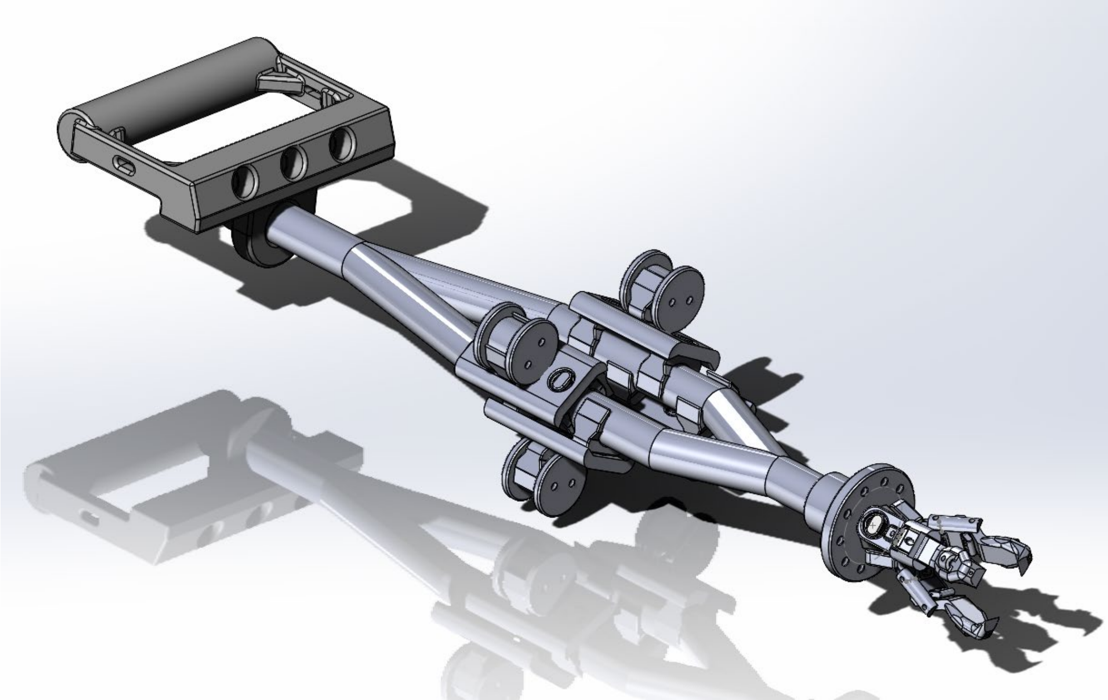
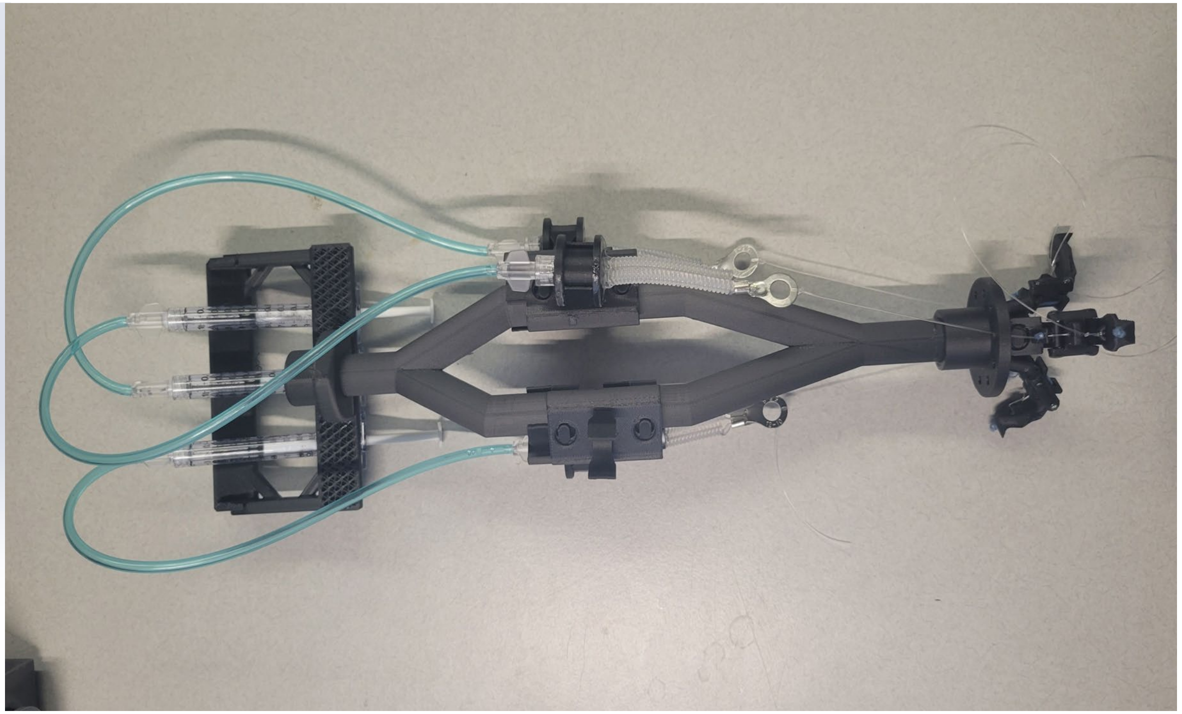


Figure 15: Individual "Finger" (Left) Bird's Claw End-Effector (Right)

Final Design: End Effector Mechanism





Budget Breakdown

Table 3: Purchasing Plan/ Budget

Item	Cost	Supplier	On Hand	Order By	Part No.	Notes
M3 Bolts	In Lab	Copper State	Yes			
M3 Set Screws	$ 8.77	Copper State	No	8-Feb		No Longer Necessary
M3 Nuts	In Lab	Copper State	Yes			
Sous Vide	Team Member Owned	Anova	Yes			
Vacuum Sealer	Team Member Owned	Guttale	Yes			
Vacuum Bags	Team Member Owned	Guttale	Yes			
3ML Syringes	$ 3.82	Qosina	Yes		C3303	Price Assumes 20ct
1ML Syringes	$ 10.47	Qosina	Yes		C3301	Price Assumes 20ct
Injection Syringe	In Lab	Amazon	Yes			
Male Luer Connector	$ 7.14	Qosina	Yes	8-Feb	11590	Price Assumes 30ct
Female Luer Connector	$ 12.45	Qosina	Yes	8-Feb	11765	Price Assumes 30ct
Tygon	In Lab	St. Goblain	Yes			3/32" OD 1/32" ID
Hydraulic Tubing	$ 12.03	Amazon	Yes	7-Feb		
Monofilament	In Lab	Trilene	Yes			20Lb Test .018" OD
Mandrel Material	In Lab		Yes			16ga Wire
Mineral Oil	In Lab		Yes			
Print Resin	Donated		Yes			
Print Filamnet	Donated		Yes			
Thread	$ 1.35	Michaels	Yes			
Epoxy	$ 6.17	Walmart	Yes			
UV Set Glue	$ 18.30	Amazon	Yes			
UV Flashlight	Included with Glue	Amazon	Yes			
Eyelet Connector	In Lab		Yes			0.25" ID
T_Slot Rail	1.96/in	Home Depot	Yes			400 & 600
T_Slot Bracket	0.89/item	Home Depot	Yes			401 & 600

Initial amount: $200

Amount spent: $49.44

- Syringes
- “luer” connectors
- small diameter tubing
- Remaining amount: **$141.56**

Future Work

Muscles

- Scaling down muscles
- Deeper materials investigation
- Higher muscle efficiency

End Effector

- Investigation into metal 3D printing for a more easily sealed and robust manifold.
- Further development of a more robust overall hydraulic system, reduce leaks and decrease head loss inside the system itself.
- Both of these could allow for larger bundles and higher work outputs.

Muscle Manufacture

- Cheaper heating method
- Long coils to cut out lengths as necessary

Questions?

References

[1] D. R. Higueras-Ruiz, M. W. Shafer, and H. P. Feigenbaum, “Cavatappi artificial muscles from drawing, twisting, and coiling polymer tubes,” *Science Robotics*, vol. 6, no. 53, 2022.

[2] “Tygon ND 100-65 Medical Tubing,” Saint-Goblain Performance Plastics, 2011. [Online]. Available: https://nau0.sharepoint.com/sites/CavatappiArtificialMuscleHand/Shared%20Documents/General/Reading%20Material/Polymer%20Actuation/Cavatappi%20Artificial%20Muscle/TYGON_ND_100-65.pdf?CT=1633130883988&OR=ItemsView. [Accessed: 15-Oct-2021]