# Team Cavatappi Final Testing Results

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# Customer and Engineering Requirements

## Customer Requirements

| | |
|---|---|
| CR1: | Design System For Muscle Fabrication |
| CR2: | Muscle Scalability |
| CR3: | Reliable Manufacture |
| CR4: | Safe to Operate |
| CR5: | Actuated in a "glove-like" mechanism |
| CR6: | Utilize bundled muscles in parallel |
| CR7: | 1.0*10^3 cm^3 max size of "hand" |
| CR8: | Flexible/ Durable |
| CR9: | Reduce leaks in muscle |
| CR10: | Cost Within Budget |
| CR11: | Develop End Effector |
| CR12: | Develop Demo |
| CR13: | Individual Finger Actuation |

## Engineering Requirements

| | |
|---|---|
| ER1: | End Effector Dimensions: 10 cm cube |
| ER2: | Muscle coil diameter (d) |
| ER3: | Cost (USD) |
| ER4: | Factor Of Safety (FS) |
| ER5: | # Muscles per Bundle (N) |
| ER6: | Muscle Length (L) |
| ER7: | Manufacturing Efficiency (%) |
| ER8: | Muscle Efficiency (%) |
| ER9: | Develop Manifold |

# QFD

| Customer Requirements (Explicit and Implicit) \ Functional Requirements | End Effector Dimensions | Muscle coil diameter (d) | Manufacturing Cost (USD) | Factor Of Safety (FS) | # Muscles per Bundle (N) | Muscle Length (l) | Manufacturing Efficiency (%) | Muscle Efficiency (%) |
|---|---|---|---|---|---|---|---|---|
| Design System For Muslce Fabrication | ○ | ○ | ● | ○ | ○ | ● | ▽ | ○ |
| Muscle Scalability | ● | ○ | ○ | ● | ● | ▽ | ● | ○ |
| Reliable | ▽ | ▽ | ○ | ▽ | ○ | ● | ○ | ▽ |
| Safe to Operate | ▽ | ▽ | ▽ | ○ | ▽ | ● | ▽ | ▽ |
| Acuated in a "glove-like" mechansim | ▽ | ● | ▽ | ○ | ○ | ▽ | ▽ | ● |
| Utilize bundled muscles in parallel | ● | ● | ○ | ● | ▽ | ▽ | ● | ● |
| 1.0*10^3 cm^3 maximum size of "hand" | ○ | ● | ▽ | ▽ | ● | ▽ | ● | ● |
| Flexible/ Durable | ○ | ▽ | ▽ | ○ | ▽ | ▽ | ● | ▽ |
| Reduce leaks in muscle | ○ | ▽ | ▽ | ○ | ▽ | ● | ▽ | ▽ |
| Cost Within Budget | ▽ | ▽ | ● | ▽ | ○ | ▽ | ▽ | ○ |
| Develop End Effector | ▽ | ▽ | ● | ▽ | ○ | ▽ | ▽ | ○ |
| Develop Demo | ▽ | ▽ | ● | ▽ | ○ | ▽ | ▽ | ○ |
| Individual Finger Actuation | ▽ | ▽ | ● | ▽ | ○ | ▽ | ▽ | ○ |

# Completed and Planned Tests

| Tests | CRS | ERs |
|---|---|---|
| Material Heating | 1,3,9 | 7 |
| Muscle Manufacture | 1,2,3,8,9 | 2,6,7 |
| Safety (Pressure) | 3,4,9 | 2,4,6,8 |
| Efficiency (Muscles) | 3,6 | 2,5,6,8 |
| Budget/ Muscle Cost | 10 | 3 |
| Device/Demo Test | 3,4,5,6,7,11,12,13 | 1 |
| -Manifold Leak Testing | 2,4,6 | 1,9 |
| -Syringe Selection Testing | 4,5,11,12 | |

# Completed Tests: Material Heating

Testing plan

- Testing was split into three testing sections
  - Undrawn/untwisted/uncoiled
  - Undrawn/untwisted/coiled
  - 2x drawn/twisted/coiled
- Section 1-Undrawn/untwisted/uncoiled
  - Utilized 170 degrees Fahrenheit as baseline temp
  - Stepped down temp by increments of 10
  - Omitted 130 and 120 temp tests because time to cook became inefficient
  - Used gathered information to generate section 2 parameters

| 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 |

# Completed Tests: Material Heating

| | | | | |
|---|---|---|---|---|
| Undrawn/coiled | 170 | 10 | 10 | Present |
| Undrawn/coiled | 160 | 25 | 10 | Present |
| Undrawn/coiled | 150 | 35 | 10 | Present |
| Undrawn/coiled | 140 | 45 | 10 | Present |

| | | | | |
|---|---|---|---|---|
| 2x drawn/twisted/coiled | 160 | 25 | 10 | Present |
| 2x drawn/twisted/coiled | 160 | 35 | 10 | Present |
| 2x drawn/twisted/coiled | 165 | 25 | 10 | Present |
| 2x drawn/twisted/coiled | 165 | 30 | 10 | Present |

Section 2-Undrawn/untwisted/coiled

- Further testing was completed at 170 for 10, 160 for 25, 150 for 35, and 140 for 45

- Section 3-2x drawn/twisted/coiled
  - Tested at 160 for 25 min
  - Tested at 165 for 30 min

- Testing yielded that the optimum cook time and temp was 165 for 30 min
  - This was based off observation of the muscle fiber after heating in the areas of flexibility, discoloration, damage, flattening of sections, and durability.

# Completed Tests: Muscle Manufacture

Muscles manufactured in different Tygon sizes

- 10 x per size, 170 °F for 30 mins
- Large: 3/16” OD, 1/16” ID
- Medium: 3/32” OD, 1/32” ID
- Small: 1/32” OD, 1/64” ID

Muscles are connected to Luer manifolds and pressurized to 100 psi

- Leaks, heating failures, mechanical failure, pressure failures

Most successful material is tested 20 additional times to estimate success rate

- Large material was most successful
- 26 successful muscles, 4 failed muscles
- **86.7%** success rate (original of ~ 40 %)

| Material | Failures | Successes |
|---|---|---|
| Small (10) | 3 Heating<br>5 Mechanical<br>2 Pressure | 0 Successes |
| Medium (10) | 2 Leaks<br>1 Mechanical<br>6 Pressure | 1 Success |
| **Large (10)** | **1 Leak**<br>**1 Mechanical** | **8 Successes** |
| **Large (20)** | **2 Leak** | **18 Successes** |

# Completed Tests: Muscle Safety (Pressure)

Tygon material is mounted to Luer connections

- Drawn to 3x length
- 15 tests cut at 5.0 cm
- Heated to 170 °F for 30 mins
- End is sealed with Epoxy

Material is pressurized to failure

- Pressure measured using LabView setup in DASL

SF calculated based on ult. and op. pressure

- $P_{avg} = \sum P_{ult} /15$
- $P_{op} = 100\ psi$
- $SF = \frac{P_{avg}}{P_{op}}$

SF = 217.33/100 = **2.17**

| Trial # | Pressure (psi) |
|---|---|
| 1 | 215 |
| 2 | 235 |
| 3 | 220 |
| 4 | 215 |
| 5 | 230 |
| 6 | 210 |
| 7 | 190 |
| 8 | 235 |
| 9 | 230 |
| 0 | 210 |
| 11 | 220 |
| 12 | 225 |
| 13 | 220 |
| 14 | 210 |
| 15 | 195 |
| Avg | 217.33 |

# Completed Tests: Total Cost

Project completed using already available materials in lab or with purchased materials remaining under the $200 budget (**$49.44**).

| 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 |

# Completed Test: Muscle Efficiency

- 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%)

**Figure 4**: Actuating Muscles

# Device/Demo Tests To Date:

**Hydraulic System Testing:**

-Excess pressure was run through the manifold with muscles attached while also hanging a 1kg weight from the bundle.

-Leaks discovered at the hydraulic connections (input side and output)

-Manifold itself was mostly watertight

-Epoxy not watertight over time. Replaced with UV cured glue that hasn't shown any degradation over time.

-"Winged" Luer connectors more brittle than previously thought and prone to cracking under stress (excess tightening force). Have backup similar barbed connectors on hand.

**Figure 5**: Female Luer Connector

# Device/Demo Tests To Date:

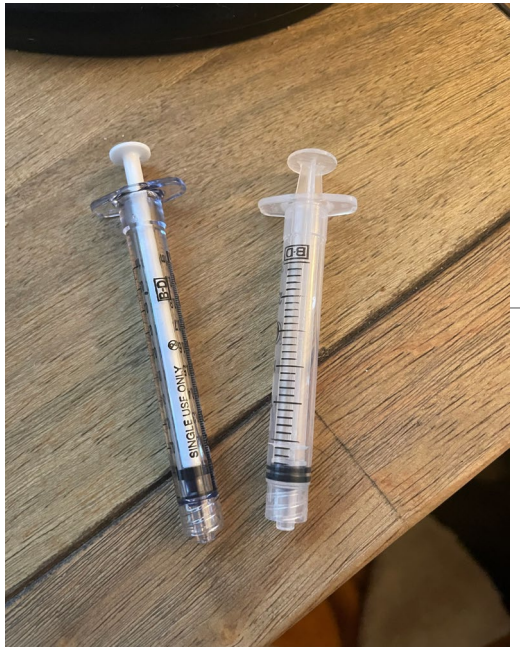



**Figure 6**: 1mL and 3mL Syringes

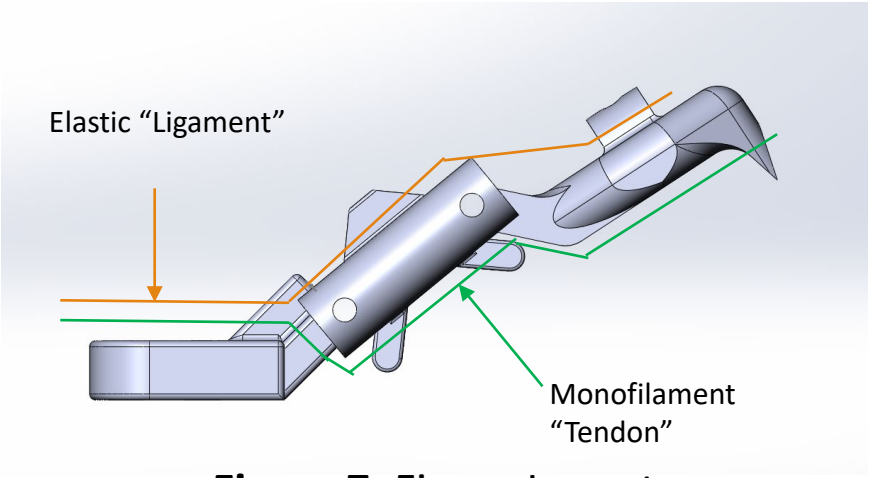



**Figure 7**: Finger Layout

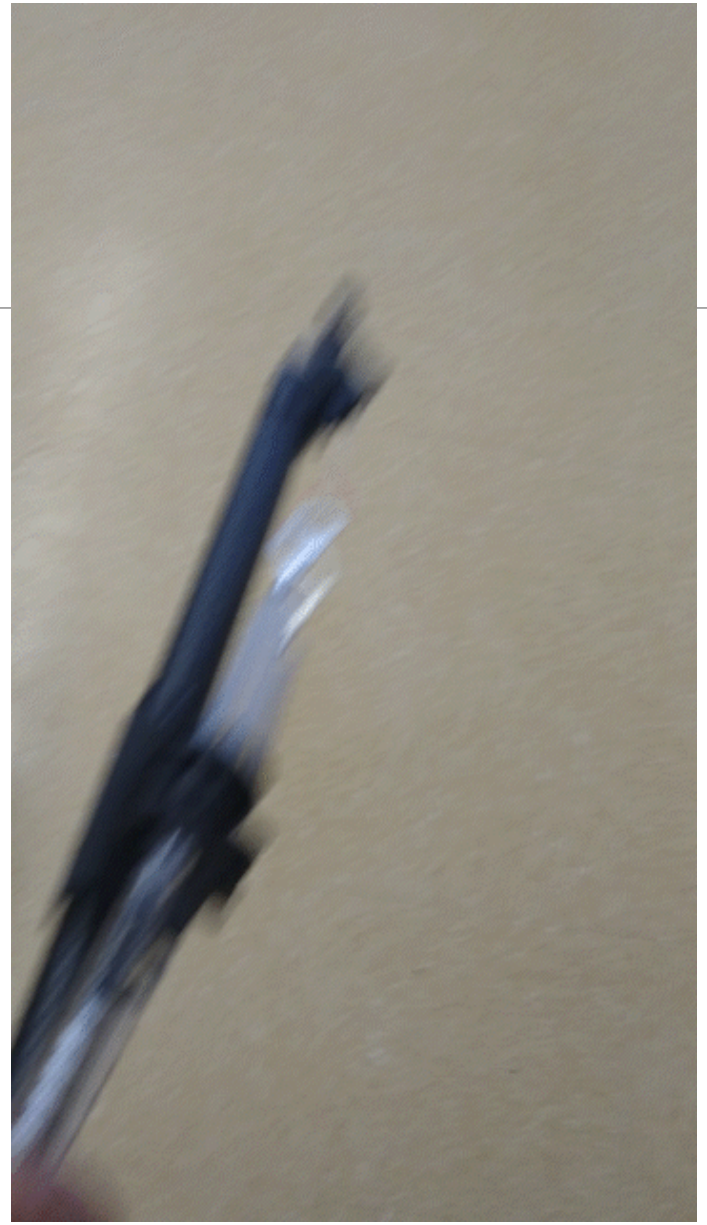
**Hydraulic Testing cont.:**

-During the manifold testing both 1mL and 3mL syringes were utilized.

- -3mL Syringes failed under pressure due to the plunger not being meant for that kind of force, caused leaking on the back end.
- -1mL Syringes worked successfully without failure, also more aesthetically pleasing and made from better materials.

**Initial Device Testing:**

- Current Elastic is too weak to counter-act the pull of the bundle without breaking.
- Physical limit need to be placed on backwards motion of squeeze-to-close end effector.



# Spec Sheet: Customer Requirements

| Engineering Requirement | Met: Yes or No | Client Acceptable: Yes or No |
|---|---|---|
| CR1: Muscle Fabrication | Yes | Yes |
| CR2: Muscle Scalability | No | Yes |
| CR3: Reliable Manufacture | Yes | Yes |
| CR4: Safe to Operate | Yes | Yes |
| CR5: “Glove-like” Actuation | No | TBD |
| CR6: Parallel Muscle Bundling | Yes | Yes |
| CR7: Hand Size < 10 cm cube | Yes | Yes |
| CR8: Flexible / Durable | Yes | TBD |
| CR9: Reduce Muscle Leaks | Yes | TBD |
| CR10: Cost Within Budget | Yes | Yes |
| CR11: Develop End Effector | Yes | Yes |
| CR12: Develop Demo | No | TBD |
| CR13: Individual Finger Actuation | Yes | TBD |

# Spec Sheet: Engineering Requirements

| Engineering Requirements | Target Value | Measured/ Calculated Value | Target Met | Client Acceptable (Yes or No) |
|---|---|---|---|---|
| ER1: End Effector Dimensions | V < 10cm^3 | 5.7cm x 6.2cm x 7.1cm | Yes | Yes |
| ER2: Muscle Coil Diameter | D < 4.5 mm | 4.5 mm | No | TBD |
| ER3: Cost (USD) | C < $200.00 USD | $49.44 | Yes | Yes |
| ER4: Safety Factor | SF = 2.0 ± 0.05 | 2.17 | Yes | Yes |
| ER5: # Muscles per Bundle | N > 1 | 2 | Yes | Yes |
| ER6: Muscle Length | None | 4.0 cm | Yes | TBD |
| ER7: Manufacturing Efficiency | Eff > 40% | 86.7% | | Yes |
| ER8: Muscle Efficiency | Eff = 20 ± 1 % | 35.6% | Yes | TBD |
| ER9: Manifold | WT @ > 100 PSI | Watertight at 160 PSI | Yes | Yes |