ME568 Lab 3: Fluidic Actuators

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I. Motivation

In this lab, we fabricated three fluidic actuators: the McKibben Pneumatic Artificial Muscle (PAM), a Fiber-Reinforced soft actuator, and a Pneu-Net bending actuator. These were later characterized based on bending angle and lifting strength, and their respective properties are discussed in detail in this report.

II. Fabrication and Experimental Setup

The fabrication of the McKibben, Fiber-Reinforced, and Pneu-Net actuators was completed by referencing the respective lab manuals for each actuator [1]–[3]. In short, the McKibben actuator was fabricated by encasing a thin tubing with a constrictive yet expandable mesh, and securing the tubing with Loctite Flexible Adhesive and zip ties (Fig. 5). The Fiber-Reinforced actuator fabrication consisted of pouring Dragonskin 10 silicone into a pre-made mold to cure in segments. Halfway through, fiber threads were wrapped around the actuator to form the reinforcement design - and a final curing step was performed to attach a strip of fabric to the bottom of this actuator (strain-limiting layer) (Fig. 7). For the Pneu-Net actuator, Dragonskin 10 was poured into a pre-made mold at intervals to form the chamber designs within the actuator (Fig. 9). The final cure consisted of adding a fabric strip to the flat bottom of the Pneu-Net as a strain-limiting layer.

All three actuators were connected to inlet tubing, and a syringe and MPRLS sensor via a T-connector configuration (Fig. 6). This testing configuration was utilized to characterize the properties of all three actuators in the following sections. For reference, Fig. 8 and 10 demonstrate to what degree each actuator was inflated to for characterization.

III. Experimental Results

A. Lab 3A: McKibben Pneumatic Artificial Muscle

In this experiment, we pressurized the McKibben using a syringe and measured the applied pressure using a MPRLS sensor, which was connected to the actuator via tubing. We monitored the contraction of the McKibben in response to the applied pressure. To calculate the percent contraction we use the formula:

$$\text{Percent Contraction} = \left(1 - \frac{\text{Actuator Length}}{\text{Maximum Length}}\right) \times 100\% \quad (1)$$

Table I shows the relationship between pressure and % contraction.

We carried out a series of three trials to measure the relationship between pressure and force. The data from these experiments are presented in the three subsequent tables, each representing the findings from an individual trial. For calculating the force generated using gathered data, we we first calculated area using the formula :

$$A = \pi\left(\frac{D_0 + b}{2}\right)^2 - \pi\left(\frac{D_0 - b}{2}\right)^2 \quad (2)$$

where D_0 is the diameter of the mesh when θ is 90 degrees (long mesh diameter) and b is the diameter of the mesh wire. For our actuator, $D_0 = 24$ mm and $b = 1$ mm. Therefore, the area A is approximately 75.398 mm². Then force is calculated by:

$$\text{Force} = \text{Pressure} \times \text{Area of the actuator} \quad (3)$$

For calculating the force defined by the Chou and Hannaford model, we used the formula:

$$F = \frac{\pi D_0^2 P}{4}\left[3\left(\frac{L}{b}\right)^2 - 1\right] \quad (4)$$

where D_0 is the diameter of the mesh when θ is 90 degrees (long mesh diameter) and b is the diameter of the mesh wire.

B. Lab 3B: Fiber-Reinforced Soft Actuator

After the fabrication process, we pressurized the fiber-reinforced actuator using a syringe. We set up a circuit with an MPRLS pressure sensor to calculate the pressure values at different volumes of air inserted by the syringe.
We conducted two experiments with this actuator. The first experiment measures the relationship between the bending angles and internal air pressure, by varying the volume of air inserted and observing how much the actuator bends and corresponding pressure values. For the second experiment, we attached weights to the actuator using Kevlar thread and recorded the largest weight the actuator could lift at different target angles, while also measuring the corresponding pressures. Table V and Table VI show the data for the two experiments conducted.

C. Lab 3C: Pneu-Net Bending Actuators

After construction, to measure the performance of the Pneu-Net actuator we ran two different experiments. First, we characterized the kinematics of the actuator by measuring actuation pressure and bending angle and relating those quantities to the volume of air injected into the actuator. Then, we tested the actuator's power by measuring the maximum weight it could lift to various angles, and the internal pressure while doing so. This data is presented in Tables VII and VIII.

IV. Discussion

A. Lab 3A: McKibben Pneumatic Artificial Muscle

Discuss your characterization of pressure vs percent contraction. Is the relationship linear? What did you observe happen to the braid angle of the mesh as the PAM was pressurized?

Using Table I we generated a graph in MATLAB illustrating the relationship between pressure and percent contraction. The graph in Fig. 1 shows that as pressure increases, the contraction also increases non linearly. Therefore the pressure vs percentage contraction relationship is not linear.

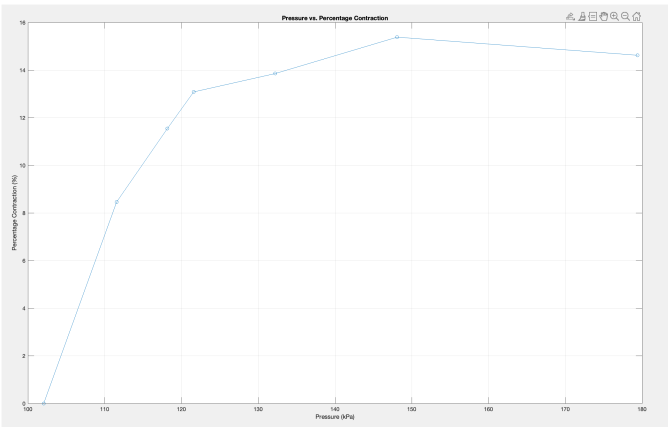

Fig. 1. McKibben: % Contraction vs Pressure

What is the length of your McKibben actuator when fully contracted (i.e. you can no longer depress the syringe)? What percent contraction does this correspond to with respect to original length?

When the actuator is fully contracted, which occurs as the syringe is compressed from 60 mL to 0 mL, the actuator's length measures 111mm. Using formula (1), we can calculate percent contraction at 111mm. Therefore the percent contraction is 14.62 %.

What are the advantages and disadvantages of using incompressible fluids (such as water) to actuate these devices? What are the advantages and disadvantages or using compressible fluids (such as air)?

Advantages of using compressible fluids (air) for actuation are:

- They provide rapid inflation of the pneumatic structure (because air has low viscosity and can be moved rapidly).
- They are light in weight and are easily controlled and measured (using regulators and sensors).
- They are almost universally available (either from compressed gas tanks or compressors).

Disadvantages of using compressible fluids (air) for actuation are:

- McKibbens utilizing air for actuation are not suitable for applications requiring high forces. This is due to the fact that air has limitations in transmitting force efficiently, which would restrict the maximum force that the McKibben can generate.
- Devices actuated by compressible fluids are susceptible to leakage due to loose tubing or sealing, which can affect the efficiency of the system.

Advantages of using incompressible fluids (water) for actuation are:

- Incompressible fluids can provide greater force transmission, therefore making it well suitable for applications requiring high force output.
- Water-actuated systems have better heat dissipation capabilities than air, which is useful for functioning in a high-temperature environment.
  Disadvantages of using incompressible fluids (water) for actuation are:
- Incompressible fluids are heavy, therefore the weight of the entire device increases, hindering the movement of the robot.

Discuss your results in terms of pressure vs force generated. How well does the behavior of your PAM align with the force-pressure model described by Chou and Hannaford?

Using Tables II, III and IV, we generated a graph in MATLAB illustrating pressure vs force generated and also the pressure vs Chou-Hannaford Model force.

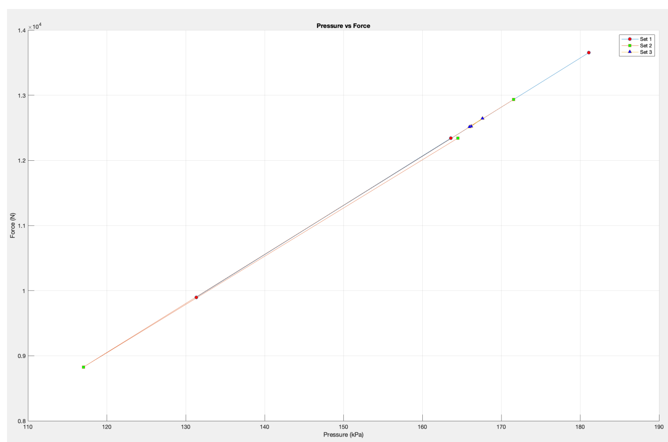

Fig. 2. McKibben: Measured Force vs Pressure for all three trials.

Figures 2 and 3 show that in both the PAM and Chou-Hannaford model, as force increases, the pressure also increases. In PAM, this trend is consistent across all three data sets which shows that the PAM's performance is predictable and consistent under varying conditions. Chou-Hannaford model shows a sharper increase in force with increasing pressure compared to the measured data by PAM.

Qualitatively speaking, how accurate is the assumption that your McKibben actuator can be modeled as a cylinder?

The Mckibben actuator can be accurately modeled as a cylinder. The geometry of the actuator resembles that of a cylinder. Additionally, as the actuator inflates, it takes up a very cylindrical shape, demonstrating a similar response to pressure in practice.

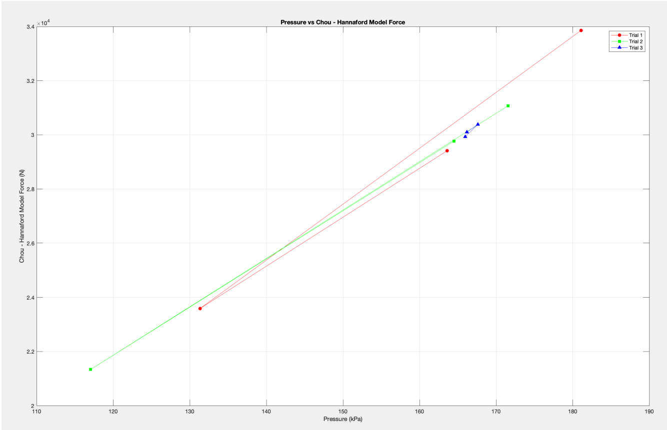

Fig. 3. McKibben: Chou-Hannaford Model Force vs Pressure for all three trials.

Discuss how you would estimate the stiffness of the actuator and how it would vary at different pressurization states (no experiments are needed here).

Stiffness can be defined as the ratio of change in force by displacement. As pressure is applied to the bladder of Mckibben actuator, it tries to expand radially. However the mesh surrounding the bladder counteracts this radial expansion, resulting in the longitudinal contraction of the actuator, thereby increasing its stiffness. Therefore, at high pressurization states, the actuator contracts and becomes stiffer. Conversely, as the pressurization decreases, the actuator becomes less stiff.

B. Lab 3B: Fiber-Reinforced Soft Actuator

Does the fiber-reinforced actuator that you tested follow a constant curvature model?

No the fiber-reinforced actuator that we tested does not follow a constant curvature model.

What impact would removing the helical threading from the actuator have on the amount of force that the actuator can generate? Why?

Removing the helical threading from the actuator could potentially reduce the amount of force it can generate. The helical threading serves to reinforce the actuator and provides structural support, allowing it to withstand higher loads and generate greater force when pressurized. Without the helical threading, the actuator may be more prone to deformation or buckling under load, limiting its ability to generate force effectively. Additionally, the helical threading can distribute force more evenly along the length of the actuator, optimizing its mechanical performance. Therefore, removing the helical threading could result in a decrease in the actuator's force-generating capabilities.

What impact would removing the fabric layer have on actuator behavior? Why?

Removing the fabric layer from the actuator would likely affect its behavior significantly. The fabric layer serves several important functions that contribute to the actuator's performance:

- Reinforcement: The fabric layer adds structural integrity to the actuator, helping it resist deformation and maintain its shape under applied loads or pressure.
- Friction Reduction: The fabric layer can reduce friction between the actuator and surrounding surfaces, allowing for smoother movement and operation.
- Flexibility Control: The fabric layer can influence the flexibility and stiffness of the actuator, affecting its range of motion and response to applied forces.

Removing the fabric layer would diminish these benefits, potentially leading to increased deformation, higher friction, and altered flexibility characteristics. Therefore, removing the fabric layer would likely have a negative impact on the overall behavior and performance of the actuator.

How would you measure the maximum force that each actuator is able to generate? Would the force generated differ if the actuator is at different bending angles?

There are 2 methods that one can use to measure the maximum force that each actuator is able to generate, these methods are described below: To measure the maximum force that each actuator can generate, you could use a force sensor or a load cell. Following is the procedure:

- Setup: Secure the actuator in a stable position, ensuring it is not obstructed and can move freely.
- Force Measurement: Attach the force sensor or load cell to the actuator in a way that allows it to measure the force exerted by the actuator during operation.
- Apply Pressure or Load: Apply pressure or load to the actuator, either manually or through a controlled mechanism such as a hydraulic system. Measure the force exerted by the actuator as it responds to the applied pressure or load.
- Record Data: Record the maximum force exerted by the actuator before it reaches its limit or begins to deform significantly. Repeat the measurement several times to ensure accuracy and consistency.

Another method one can use is measuring the maximum force generated by the actuator. Here is how one can do it:

- Setup: Secure the actuator in a stable position, ensuring it won't move or slip during testing.
- Load Application: Apply a gradually increasing load to the actuator. This load could be in the form of weights or any other objects with known mass.
- Observation: Continuously monitor the actuator as you add weight. Note any signs of deformation or failure.
- Max Load: Identify the maximum load the actuator can hold without failing or deforming beyond acceptable limits.
- Force Calculation: Once you've determined the maximum load, you can calculate the force exerted by the actuator using the formula: Force = Mass × Acceleration due to gravity (F = m × g), where 'm' is the mass of the load and 'g' is the acceleration due to gravity (approximately 9.81 m/s²).

This method provides a direct measurement of the maximum load capacity of the actuator and allows you to calculate the corresponding force. It's important to ensure that the actuator is loaded gradually to avoid sudden failure or damage.

Additionally, consider performing multiple trials to ensure consistency and accuracy of your measurements.

Regarding the second part of the question, yes, the force generated by the actuator may differ at different bending angles. This difference is primarily due to changes in the actuator's mechanical properties, such as stiffness and leverage, as it bends. At different bending angles, the actuator may experience variations in force output due to changes in its geometry and the distribution of stresses within the material. Therefore, it's important to consider the bending angle when evaluating the force characteristics of the actuator.

Can you try to estimate the speed of actuation and compare it to other actuators?

Comparing the speed of the actuation of all the 3 actuators with each other is as follows:

- The speed of Fiber-Reinforced actuator is near about same as of the Pneu-Net Bending actuator, but it is more that of the McKibben Pneumatic actuator made in section 3A of the lab.

C. Lab 3C: Pneu-Net Bending Actuators

Do the actuator that you tested follow a constant curvature model? Do the actuator segments inflate uniformly, or do some bend more than others at the same pressure? Whichever it may be, speculate as to why your actuator behaves in this manner.

We observed the Pneu-Net actuator having very constant curvature along its entire length, bending in a very regular circular manner. This indicates that the segments are all inflating uniformly. We took care to ensure the casting and fabrication of this actuator was as precise as possible, and did significant post processing to ensure a regular shape with no extra material or bubbles. We believe the care put into the manufacturing ensured that the individual chambers along the actuator all had very similar dimensions, internal volumes and wall thicknesses, leading to very uniform inflation of all segments under the same pressure.

How do the bending angle versus pressure curves of each actuator compare to ones from the fiber reinforced actuator?

In figure 4 below we can compare the bend angle vs pressure curves of both the fiber reinforced actuator and the Pneu-Net actuator. Although both have similar shape, there are a few notable differences. The first is that the Pneu-Net actuator (in red) can reach larger bending angles with significantly less pressure, being able to bend as much as the fiber reinforced actuator with only 50-60% of the pressure in some cases. The second is that the Pneu-Net actuator was also able to bend more, although the difference is not significant enough to rule out that higher quality fabrication could be the culprit. Most interestingly perhaps, is the fact that not only did the Pneu-Net actuator achieve the same bend angles with significantly less pressure, it was also able to support much larger weights at those angles. This suggests that the Pneu-Net actuator had a much larger force-to-pressure ratio, meaning that more of the pneumatic force is transferred into useful work, making it significantly more efficient than the fiber reinforced actuator.

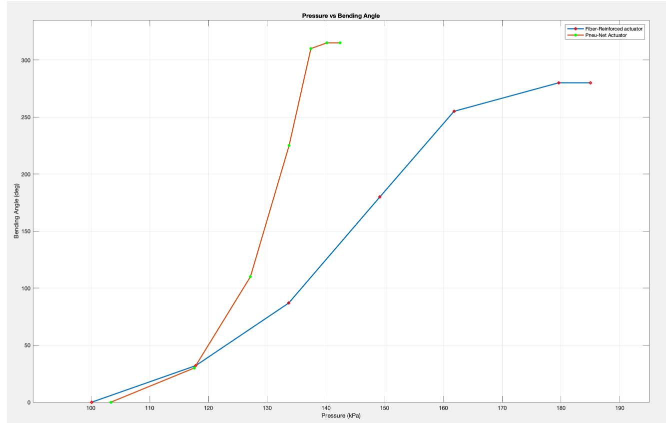

Fig. 4. Bend Angle vs Pressure curve - Fiber Reinforced vs Pneu-Net

How would you measure the maximum force that each actuator is able to generate? Would the force generated differ if the actuator is at different bending angles?

While the testing with weights is illuminating, the maximum force the actuator generates could be better characterized by using an experimental setup that prevents it from bending beyond the intended angle. The internal pressure could then be increased without having the actuator expand more, which will yield more accurate (and probably larger) values for maximum strength at different angles. By the same idea, it would be interesting to see whether the maximum force generated at different bend angles increases or decreases with larger bend angles. But a reasonable idea is that smaller bend angles might achieve larger maximum forces given that less pressure is "wasted" reaching that angle, and thus more pressure can be converted to force.

References

[1] *ME568 Lab 3A - McKibben Pneumatic Artifical Muscle*.
[2] *ME568 Lab 3B - Fiber-Reinforced Soft Actuator*.
[3] *ME568 Lab 3C - Pneu-Net Bending Actuators*.

Appendix A
Additional Figures and Tables

TABLE I
PRESSURE VS % CONTRACTION

Input: Syringe Volume (mL)	Pressure (kPa)	Actuator Length (mm)	% contraction
60 (60 to 00)	179.41	111	14.62%
50 (60 to 10)	148.10	110	15.38%
40 (60 to 20)	132.20	112	13.85%
30 (60 to 30)	121.59	113	13.08%
20 (60 to 40)	118.16	115	11.54%
10 (60 to 50)	111.56	119	8.46%
60 (60 to 60)	102.06	130	0.00%

TABLE II
TRIAL 1: PRESSURE VS FORCE

Mass (g)	Pressure (kPa)	Actuator Length (mm)	Force (N)	Chou-Hannaford Force(N))
100	163.62	114	12342.68	29416.07
200	131.33	125	9898.59	23585.33
500	181.08	122	13653.43	33852.81

TABLE III
TRIAL 2: PRESSURE VS FORCE

Mass (g)	Pressure (kPa)	Actuator Length (mm)	Force (N)	Chou-Hannaford Force(N)
100	164.50	114	12342.52	29770.34
200	117.05	125	8827.84	21336.86
500	171.56	115	12935.55	31073.70

TABLE IV
TRIAL 3: PRESSURE VS FORCE

Mass (g)	Pressure (kPa)	Actuator Length (mm)	Force (N)	Chou-Hannaford Force(N)
100	166.19	113	12521.92N	30102.82N
200	167.60	118	12643.71N	30378.77N
500	165.97	115	12516.71N	29930.13N

TABLE V
PRESSURE VS BENDING ANGLE

Syringe Volume (mL)	Pressure (kPa)	Actuator Bend Angle (deg)
60 (60 to 00)	N/A	N/A
50 (60 to 10)	179.60	280
40 (60 to 20)	161.78	255
30 (60 to 30)	149.17	180
20 (60 to 40)	133.66	87
10 (60 to 50)	117.80	32
60 (60 to 60)	100.11	0

TABLE VI
PRESSURE VS MAX. WEIGHT LIFTED

Bending Angle (deg)	Pressure (kPa)	Max Weight Lifted (g)
30º	159.71	50
45º	144.52	20
60º	145.85	20

TABLE VII
PRESSURE VS BENDING ANGLE

Syringe Volume (mL)	Pressure (kPa)	Actuator Bend Angle (deg)
60 (60 to 00)	142.41	315
50 (60 to 10)	140.14	315
40 (60 to 20)	137.42	310
30 (60 to 30)	133.71	225
20 (60 to 40)	127.13	110
10 (60 to 50)	117.58	30
60 (60 to 60)	103.37	0

TABLE VIII
PRESSURE VS MAX. WEIGHT LIFTED

Bending Angle (deg)	Pressure (kPa)	Max Weight Lifted (g)
30º	144.82	150
45º	144.78	120
60º	143.24	100

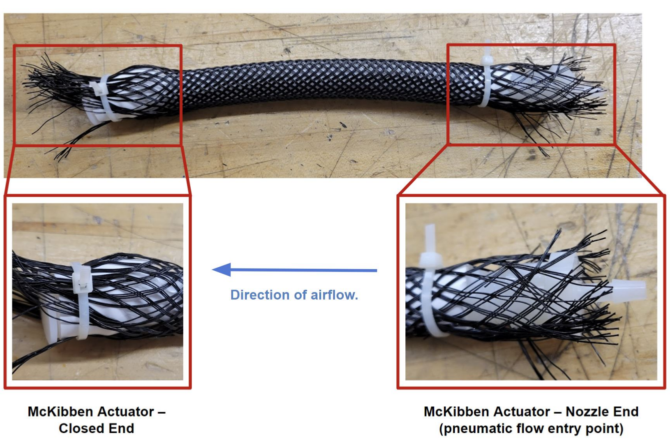

Fig. 5. McKibben actuator after fabrication.

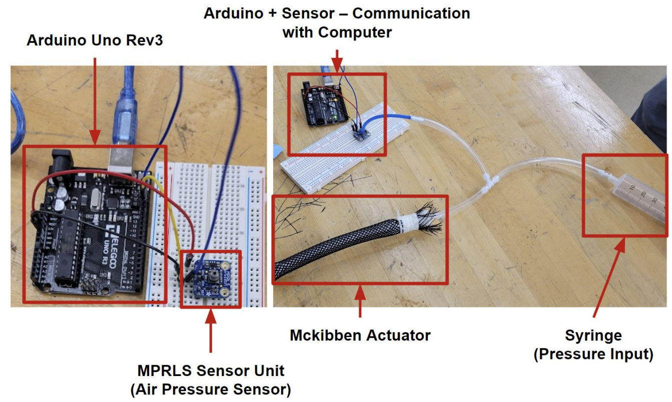

Fig. 6. McKibben testing setup. Utilized this same testing setup for both the Fiber-Reinforced and Pneu-Net actuators.

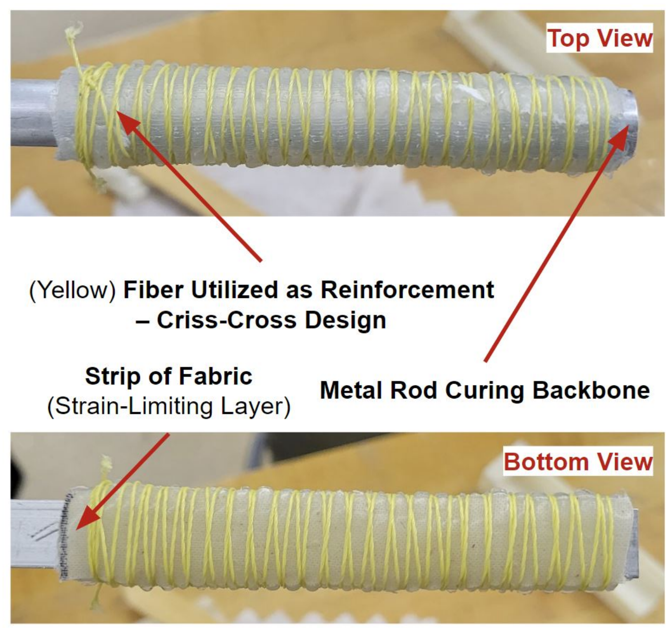

Fig. 7. Fiber-Reinforced actuator during fabrication. This picture was taken before the final cure. Note how the fibers form criss-cross designs across the length of the actuator.

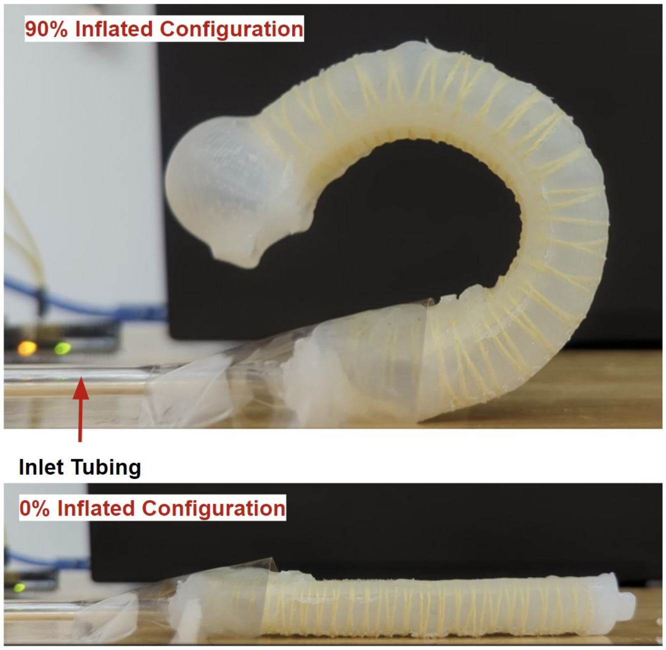

Fig. 8. Fiber-Reinforced actuator at approximately 90 and 0 percent inflation.

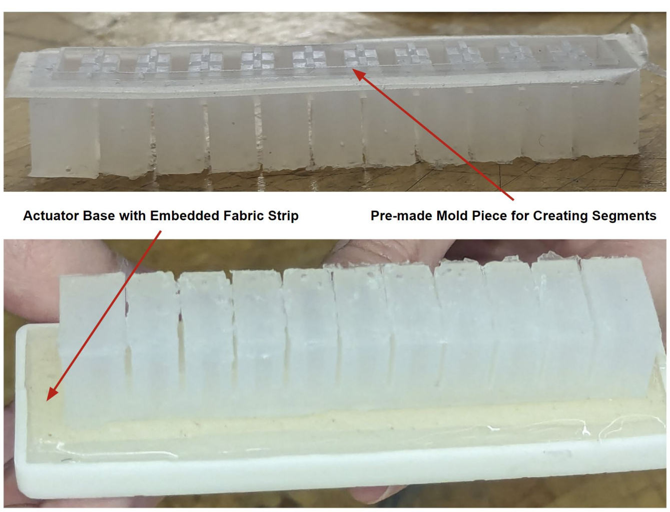

Fig. 9. Pneu-Net actuator mid-fabrication.

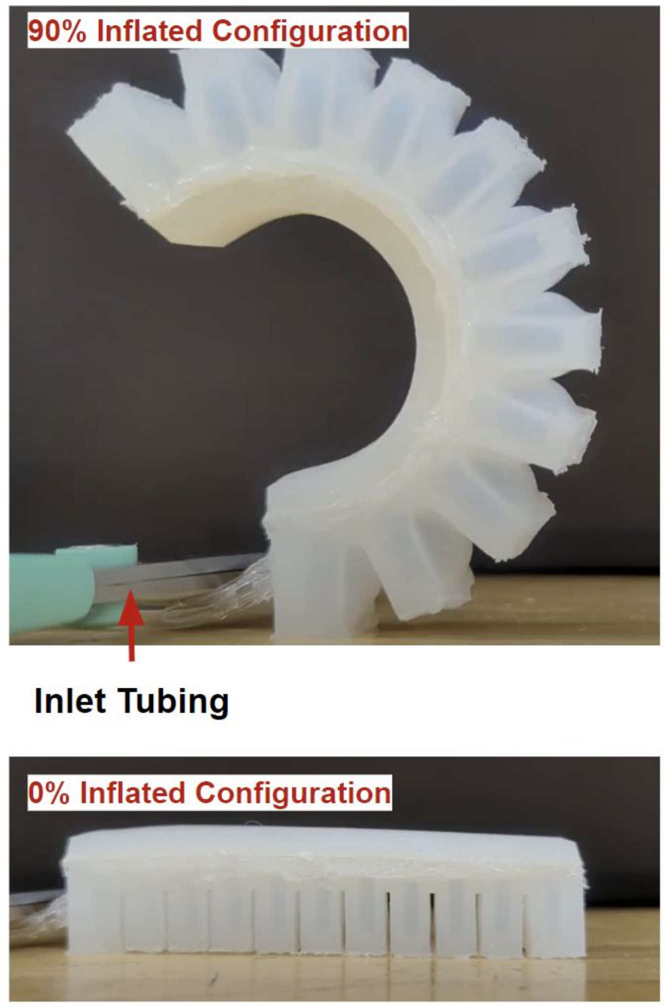

Fig. 10. Pneu-Net actuator at approximately 90 and 0 percent inflation.