# Novel Embroidered Actuator Fabrication and Design Optimization

by

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ABSTRACT

McKibben actuators have extensive applications in soft robotics and wearables; however, traditional manufacturing processes limit their ability to tailor design parameters to specific applications. This thesis explores a novel fabrication method for these actuators: using an embroidery machine to create the 'outer mesh,' thus allowing for variation of backing material and embroidery pattern. Having tested and iterated through six assembly processes, the most reliable method is presented, beginning with digital embroidery pattern creation and concluding with the final actuator assembly. Additionally, the actuators are characterized to illustrate how varying the design parameters affects performance. The effect of pressure on actuator movement is explored, and it can be seen that as pressure increases, actuator curvature increases. Out of the three embroidery backing materials explored – felt, cotton, and polyester – felt had the greatest curvature until 24psi, beyond which polyester surpasses it. This work also shows that the addition of embroidery onto the backing material decreases curvature and that varying the embroidery patterns results in different decreases. The resulting curvatures in all these experiments demonstrate how the response of embroidered actuators can be tailored to meet the design requirements for specific uses. Finally, different applications of these actuators are explored, and a robotic hand for which the actuators have been used as fingers is shown.

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# 1. Introduction

## 1.1 Overview of Pneumatic McKibben Actuators

A McKibben air muscle is a type of actuator used in soft robotics Some key advantages of these actuators include their lightweight design, low cost, and lack of moving parts. [1][2] They can be used in robotic hands, integrated into wearables, and act as simulators of organs. [3] Invented in the 1950s, they consist of a tube, mesh, end plates, and clamps, resulting in a device that can be pressurized to achieve linear motion. A standard design is shown in Figure 1.

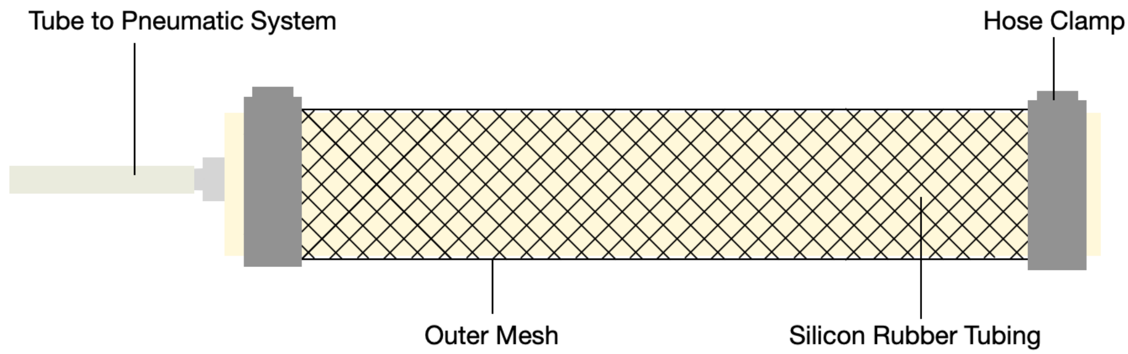



**Figure 1:** A standard pneumatic McKibben actuator consisting of an inner tube, outer mesh, internal end plates, and hose clamps. The actuator is connected to a pneumatic system to allow pressurization.

## 1.2 Motivation For Embroidered McKibben Actuators and Prior Work

Despite the existing popular design, there is room for improvement and the potential to incorporate novel manufacturing methods into the actuators. Currently, according to Chou and Hannaford's model, the force from the actuator, and thus its linear motion, is controlled by input pressure as well as the outer mesh's diameter and braid angle. [4] Thus, to vary actuator performance, the outer mesh should be changed. These outer meshes are industrially manufactured and thus must be bought, meaning that actuator design flexibility can be difficult to achieve.

Replacing the outer mesh with an embroidered component would give greater control over design parameters, enabling the designer to use digital fabrication to rapidly create actuators with varied responses to pressurization. Key embroidery features that can be changed include backing material type, embroidery pattern, thread type, and additional embroidery patterns on the backing material. The motion of these actuators would be more curved when compared to the traditional version as the bottom side is much more heavily constrained by the base material than the top is by the tread.

A significant body of work exists on alternative actuator manufacturing methods; Luo et al. (2022) explore digital fabrication and the use of a knitting machine to create pneumatic actuators with integrated sensing capacities. [5] Development of the embroidered McKibben actuator builds upon this work as they would share many applications with the knitted actuators; however, embroidery would allow quicker outer 'mesh' creation and the use of a backing material facilitates greater curvature. Other existing work on embroidered actuators focuses on circular inflatable actuators [6] or very thin linear actuators that are integrated into a large plane of fabric. [7] The novel actuators designed in this thesis focus on how to utilize the current structure of the pneumatic McKibben actuators, while providing improved design flexibility.

# 2. Actuator Design and Manufacturing

### 2.1 Design Requirements and Challenges Faced

Designing a successful embroidered actuator and manufacturing process required key design features: the actuator must have relatively repeatable deformation, consist of readily available parts, and have the potential to be fabricated at various lengths. In terms of manufacturing requirements: assembly time should be minimized and the outer 'mesh' must be fabricated on a standard commercial embroidery machine.

Throughout the iterative design process, many challenges arose. Initially, the manufacturing workflow involved embroidering over the inner silicon tube to reduce assembly time. However, it proved difficult to hold the tube precisely and securely, resulting in many failures when the embroidery needle punctured the silicon tube. Additionally, large gaping occurred between the silicon tube and threads due to the inability to get the needle consistently close enough to the silicon tube without puncturing it. Figure 2 exhibits this issue.

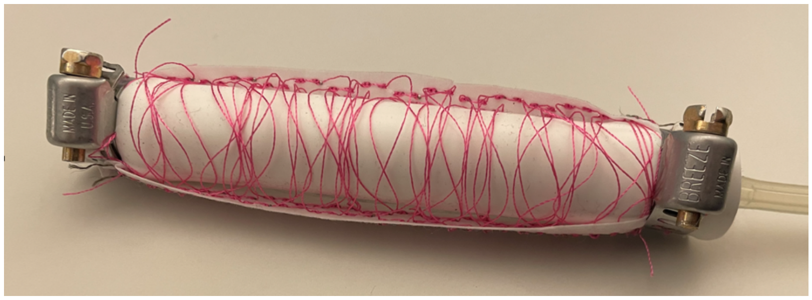
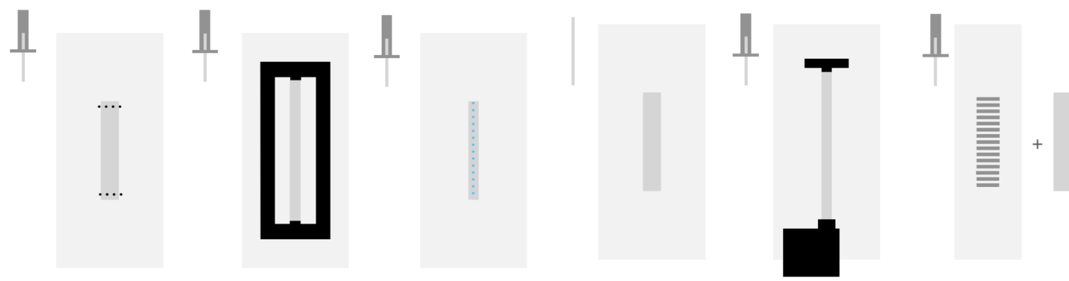


**Figure 2:** An early prototype exhibiting large gapping between the embroidery thread and the silicon tube. This image was taken after initial pressurization tests, and the problem was exacerbated by usage.

Table 1 shows the various approaches that were tested to solve these problems. These strategies included: fixturing with embroidery, stretching the tube in a jig, including tape inside the tube, removing the presser foot, sucking air from the tube, inserting the tube post-embroidery. Each option was evaluated on the four following metrics: effectiveness of stopping gapping, manufacturing efficiency, process complexity, and cost. Figure 3 shows some images from testing. Only post-embroidery insertion of the silicon proved successful in completely eliminating thread gapping and tube puncturing.

**Table 1:** A tradeoffs table showing the six different options for reducing thread gapping and puncturing of the inner tube. Each method is rated on four different metrics – effectiveness of solving the issues, manufacturing efficiency, process complexity, and cost. Red indicates that the solution cannot successfully meet the metric. Yellow indicates that the solution isn't ideal; however, it is sufficient. Finally green indicates that the solution is good for meeting the metric. The final option, post-embroidery insertion of the silicon tube has the highest rating, receiving three green bubbles and one yellow.



| | Fixturing the Silicon Tube with Embroidery | Stretching Jig For the Silicon Tube | Tape Inside the Silicon Tube | No Presser Foot on the Embroidery Machine | Suck Air Out from the Silicon Tube | Post-embroidery Insertion of the Silicon Tube |
|---|---|---|---|---|---|---|
| Effectiveness at Reducing Gapping | Gapping (red) | Spring Back (red) | Doesn't Hold (red) | Some Gapping (yellow) | Insufficient (red) | No Gapping (green) |
| Manufacturing Efficiency | One-step (green) | Attachment (yellow) | Attachment (yellow) | One-step (green) | Attachment (yellow) | Insertion (yellow) |
| Process Complexity | No fixtures (green) | Fixture on bed (yellow) | No fixtures (green) | Breakages (yellow) | Chaos on bed (red) | No fixtures/tube (green) |
| Cost | Low (green) | Medium (yellow) | Low (green) | Low (green) | Medium (yellow) | Low (green) |

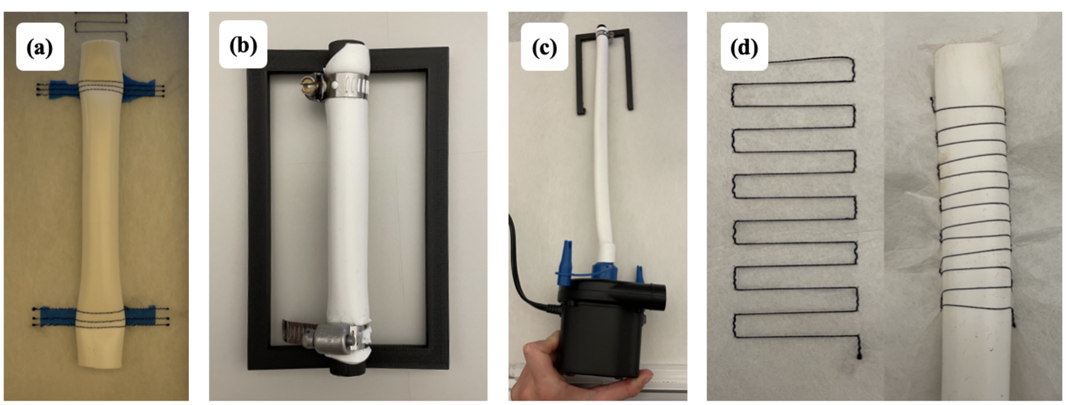



**Figure 3:** Images of four of the different solutions tested to solve the gapping issue: (a) embroidery of the silicon tube, (b) use of a stretching jig, (c) sucking air out of the silicon tube, (d) post-embroidery insertion of the silicon tube. Option (d) was the optimal path forward.

## 2.2 The Final Design

After working through these challenges and moving forward with post-embroidery insertion of the inner silicon tube, the final design was created. The result can be seen in Figures 4 and 5.

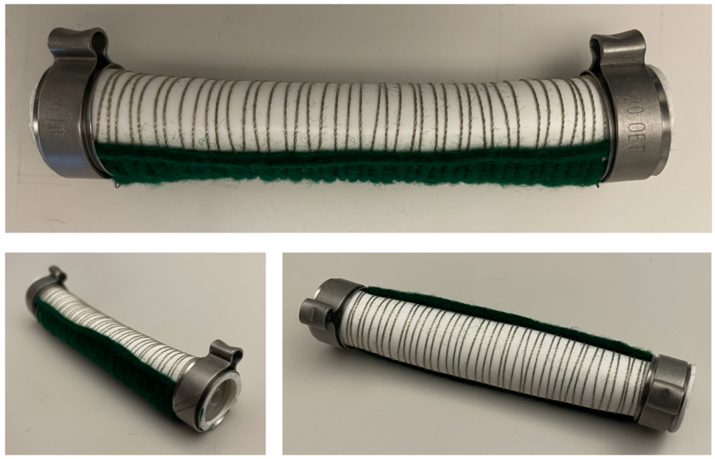


**Figure 4:** The final design of the embroidered actuator. The design is neat and lacks any thread gapping. Additionally, it has secure clamps on both ends around cylindrical acrylic pieces, one of which is threaded to connect to a barb fitting and pneumatic system.

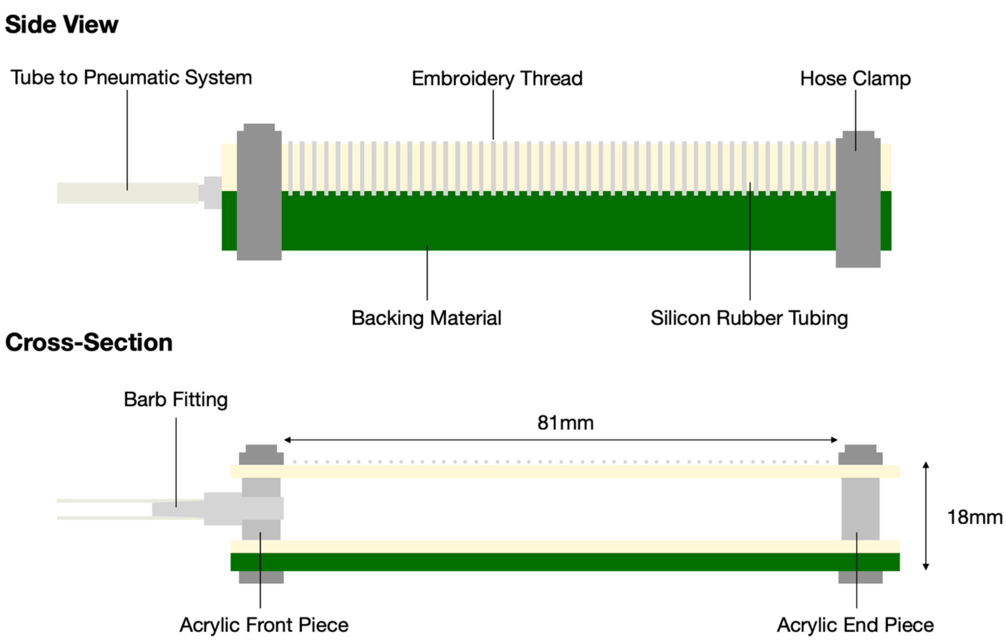



**Figure 5:** The side view and cross section of the embroidered actuator. This illustrates the various components required and how they are assembled and connected to the pneumatic system.

### 2.3 Manufacturing – Embroidery

Embroidering is a key part of the actuator manufacturing process and a series of steps are required to generate the file needed for the embroidery machine. Table 2 explains this process. These actuators were made on a Tajima commercial embroidery machine (TMEZ-SC1501). Figure 6 shows the embroidered pattern at three different stages of the process. First, as a drawing in Inkscape, then as an embroidery simulation using Ink/Stitch, and finally as the finished embroidered part from the machine.

**Table 2:** The eight-step process of creating the embroidered 'outer mesh' of backing material and thread. The process uses Inkscape and a Tajima commercial embroidery machine (TMEZ-SC1501).

| | |
|---|---|
| **Step 1** | Launch Inkscape with the Ink/Stitch extension installed |
| **Step 2** | Draw out embroidery pattern, change all lines to dotted, and 'stack' lines chronological order |
| **Step 3** | Adjust the Ink/Stitch 'params' to set stitch lengths, lock stitches, and view the stitch simulation |
| **Step 4** | Export the file as a .dst and then import it into a python library |
| **Step 5** | Convert the .dst file to a .txt file |
| **Step 6** | Delete all 'cut' stitches so the machine will not cut the thread at any point |
| **Step 7** | Convert the new .txt file back to a .dst and load this onto the embroidery machine |
| **Step 8** | Attach backing material, position the needle, and start the machine |

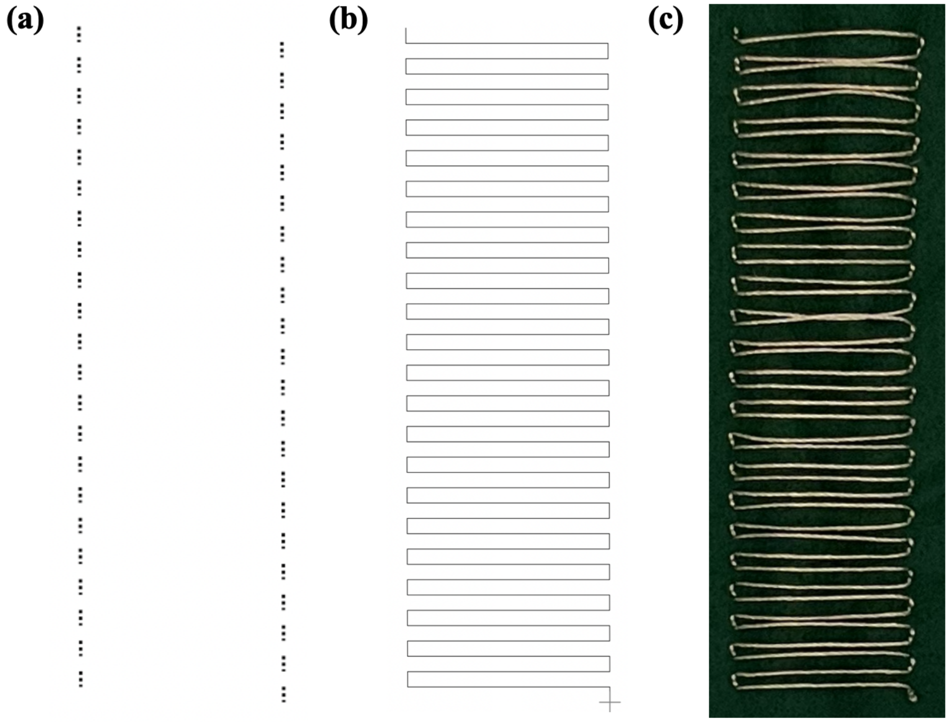



**Figure 6:** Three stages of the embroidery process: (a) the initial Inkscape drawing – Step 2, (b) The Ink/Stitch simulation – Step 3, (c) the embroidered 'outer mesh' that is ready for integration into the actuator – Step 8.

## 2.4 Manufacturing – Assembly

The assembly process is similar to that of traditional McKibben actuators; however, the insertion of the inner tube takes slightly more time. Overall, the process takes approximately five minutes per actuator. After embroidering thread onto the backing material, the inner silicon rubber tubing is folded and inserted between this thread and backing material. Velostat, a slippery material, is used to guide the silicon tube into place. The tape on the silicon tube is cut, allowing the tube to unfold. Then, the tube and thread section are cut out of the backing material. Finally, full assembly can be completed by fixing an acrylic spacer on each end with hose clamps to hold them into place. Although these actuators take slightly longer to assemble than the traditional ones, the flexibility and design variability that they offer is exciting.

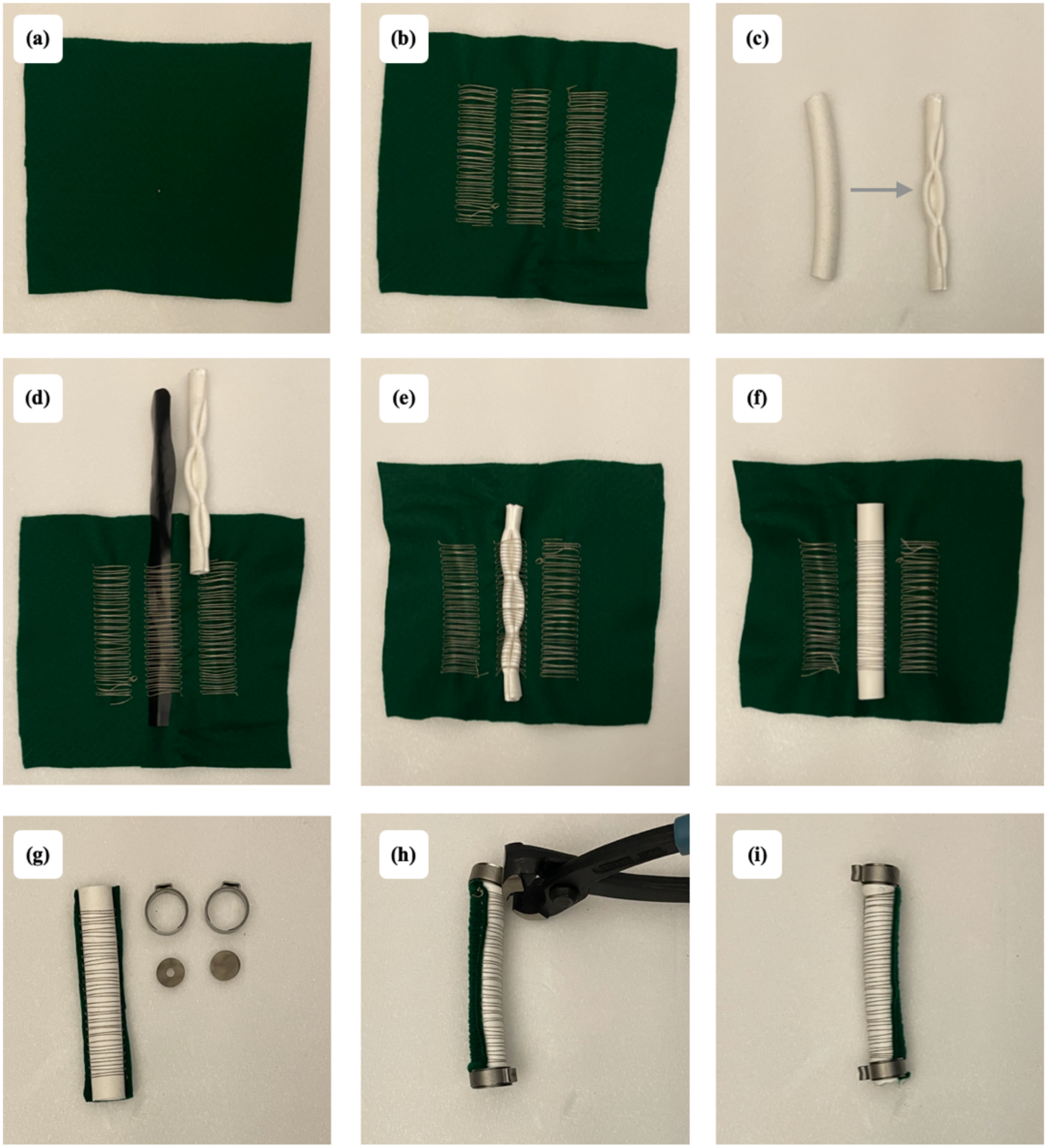



**Figure 7:** The different steps of the assembly process are shown: (a) gather backing material, (b) embroider the pattern for the outer ‘mesh’, (c) fold and secure the inner silicon tube with tape, (d) insert the Velostat piece into the embroidered outer ‘mesh’, (e) use the Velostat piece to slide the silicon tube into embroidered outer ‘mesh’, (f) unfold the tube and ensure all threads are carefully positioned, (g) cut out around the silicon tube and gather the acrylic pieces and hose clamps, (h) insert the acrylic pieces and tighten the hose clamps, (i) the actuator is complete.

# 3. Actuator Characterization – Experimental Design

### 3.1 Experimental Design

Analyzing the displacement of the actuators under pressure is a key step to understanding their functionality. The experimental setup illustrated in Figure 8 allows the actuator to be clamped in a bench vice, with one end fixed in place, and pressurized with a pneumatic system. A video camera is positioned in front of the setup with the same view as Figure 8. This approach allows the capture of the actuation; thus, the displacement of the end of the actuator (the blue dot) can be measured using video analysis on WebPlotDigitizer. Additionally, it can extract the lines of curvature, which allows further plotting and comparison in MATLAB.

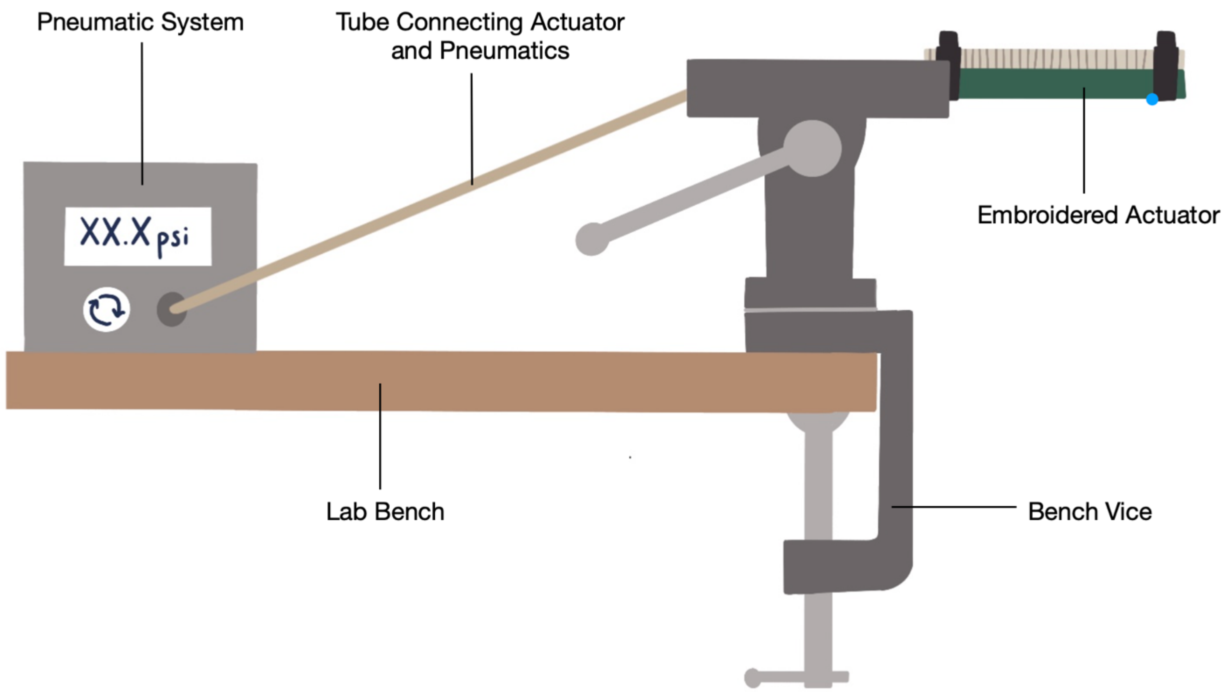



**Figure 8:** The experimental setup showing the actuator clamped in place and connected to the pneumatic system. The video camera is ready to capture the movement of the actuator and the blue dot at the end in particular.

### 3.2 Parameters to Investigate

Four relationships were investigated during this experiment: the connection between pressure and displacement, backing material and displacement, embroidery on the backing material and displacement, and repetitive use and displacement. Ten different actuators were required for these experiments, as shown in Table 4. Prior testing was conducted to confirm that the displacement of the actuator is relatively consistent across two identical actuators, and thus only one trial is needed for each actuator type. Each actuator was made with identical components, apart from the backing materials, and is the same length.

**Table 3:** The ten different actuators used during the experiments. These ten actuators will facilitate the investigation of four different relationships relating to pressure, backing material, cycle testing, and embroidery on backing.

| | | | | |
|---|---|---|---|---|
| **Pressure and Backing Material Variation** | Felt | Cotton | Polyester | |
| **Cycle Testing** | Felt | Cotton | Polyester | |
| **Embroidery on Backing** | Plain | Horizontal Lines | Vertical Lines | Criss-Cross Lines |

# 4. Actuator Characterization – Results and Discussion

## 4.1 The Effect of Pressure and Backing Material

Pressurization and backing material play a large role in actuator performance as they directly influence the direction and degree of movement. Three different backing materials, cotton, felt, and polyester were tested to analyze and compare their displacement as pressure increases.


**Figure 9:** Three different fabrics (cotton, felt, polyester) integrated into embroidered actuators. The displacement of the actuators at a pressure of 30psi can be seen.

To further analyze how the internal pressure affects the actuator, Figure 10 shows deflection as the pressure of the actuators increases from 0 to 30psi. For all materials, the actuator starts straight and gradually increases in curvature.

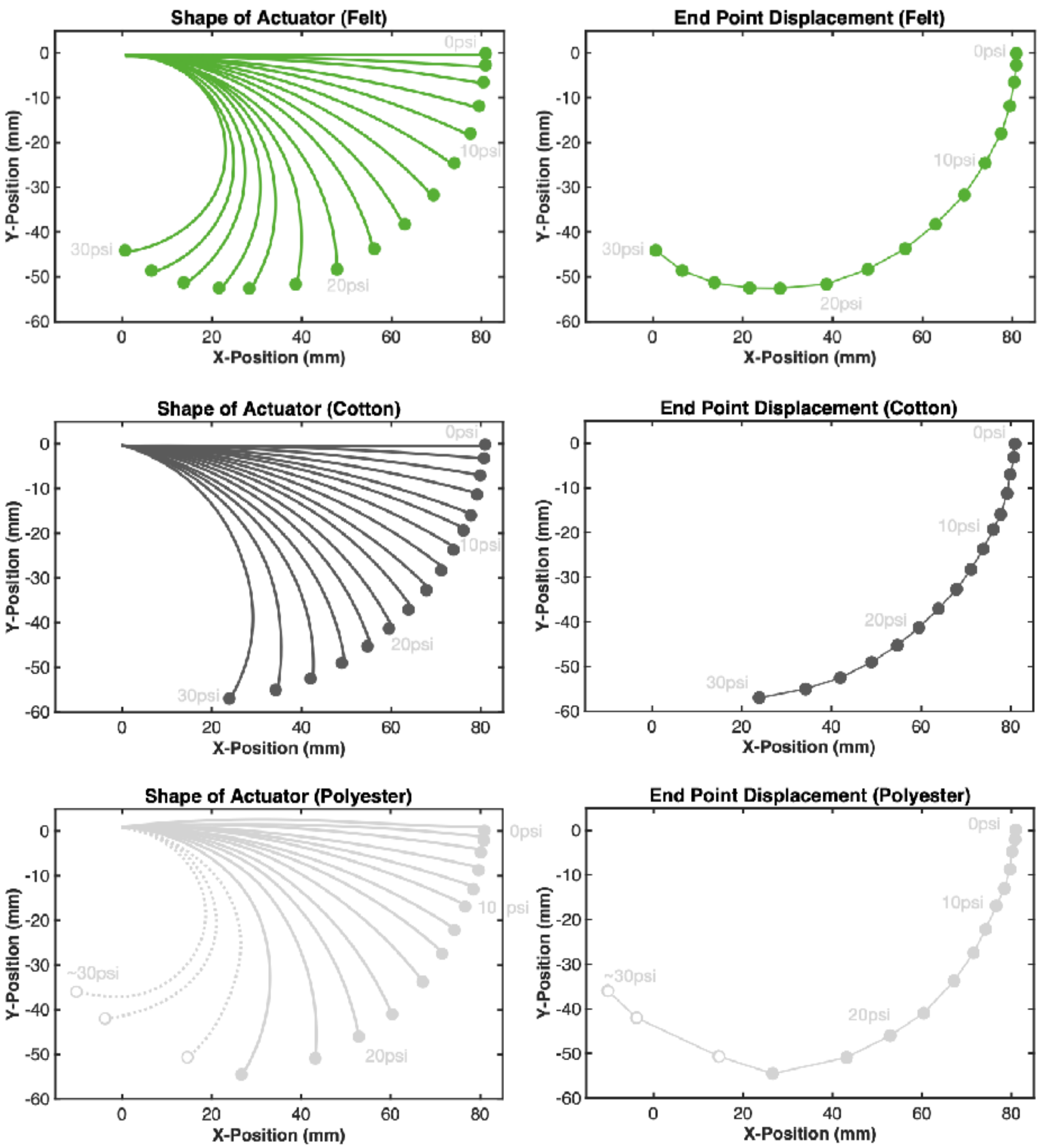



**Figure 10:** Having integrated three different fabrics, felt (green), cotton (dark gray), and polyester (light gray), into embroidered actuators, the displacement of the actuators at pressures from 0-30psi can be seen. The dotted lines and circle outline for polyester indicates that the actuator did not settle at one exact position, and continued to bend as the pressure was held for longer.

These individual pressure responses are interesting to observe as they can be used to design the input pressure needed for a specific actuator displacement. However, comparing the performances of the different fabrics provides more insight into materials selection. Figure 11 shows us the performance of the different materials at a uniform pressure (24psi).

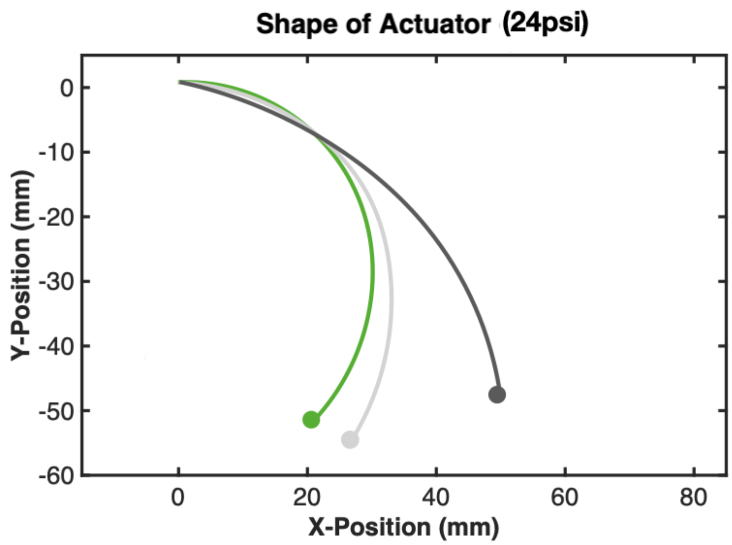



**Figure 11:** The displacement of three different actuators, felt (green), cotton (dark gray), and polyester (light gray), at 24psi. The felt shows the greatest displacement followed by polyester and then cotton. This is an example of the differences in curvature based only on backing material

For 0-24psi, felt has the greatest curvature; however, as the pressure goes above 24psi the polyester backing undergoes constant increasing of curvature and thus surpasses felt. At higher pressures (14+ psi), cotton is always the least curved. At lower pressures, the difference between the three materials is much less notable. In order to understand the material theory behind these results, testing was conducted on an uniaxial mechanical tester to quantify the material properties – specifically the Young's modulus. Figure 12 exhibits the stress-strain curves for felt, cotton, and polyester. Polyester has the highest Young's modulus (125,000 Pa), making it the stiffest material, followed by felt (5300 Pa), and then cotton (6112 Pa).

The pattern of increasing Young's modulus (felt to cotton to polyester) does not match with the typical order of increasing curvature (cotton to polyester to felt). Although a relationship between Young's modulus and curvature cannot be derived at this time, the difference in actuator movement is clear from Figures 10 and 11.

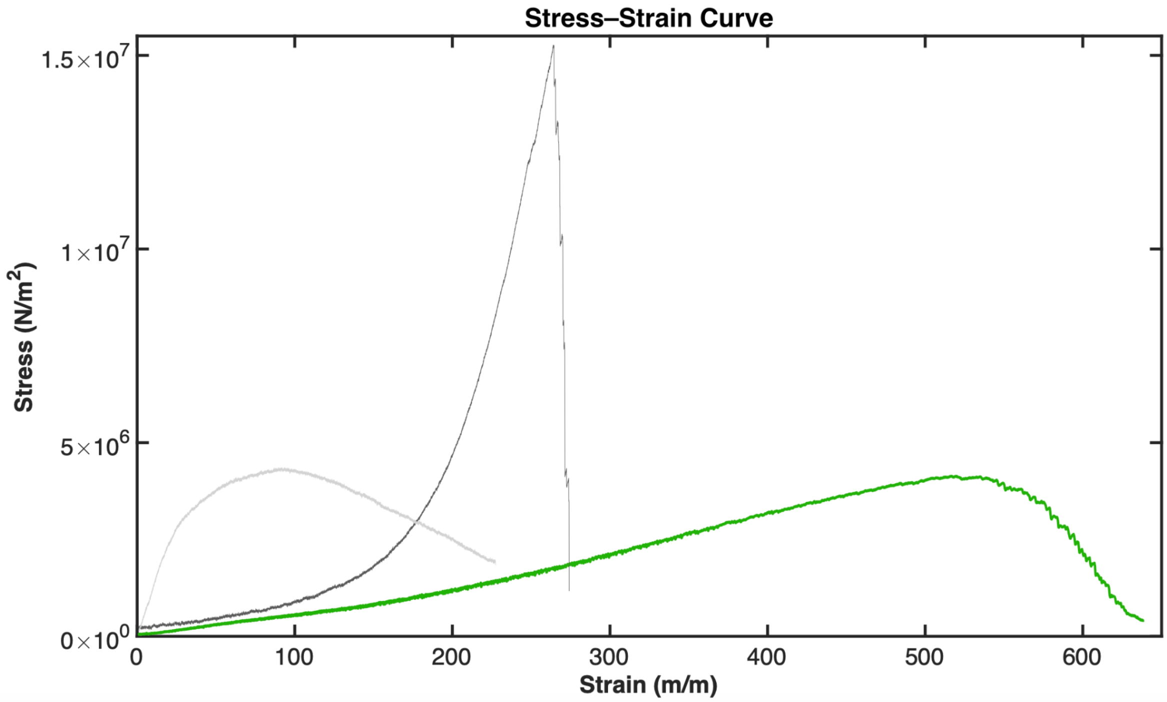



**Figure 12:** The stress strain curves for felt (green), cotton (dark gray), and polyester (light gray) from tensile test on a uniaxial mechanical tester. The young's modulus for each material is calculated from the initial straight portion of the it's respective stress-strain response. Felt has a young's modulus of 5300 Pa, Cotton of 6112 Pa and Polyester of 125000 Pa.

### 4.2 The Effect of Embroidery on the Backing Material

One major advantage of the embroidery machine is the opportunity for customization. By embroidering on the backing material (separate to the outer tube embroidery), there is potential for greater design variation. Figure 13 shows the three different embroidered actuators, one with horizontal lines, one with vertical lines, and one with criss-cross lines. Figure 14 explores and compares the response of these different patterns at 20psi.

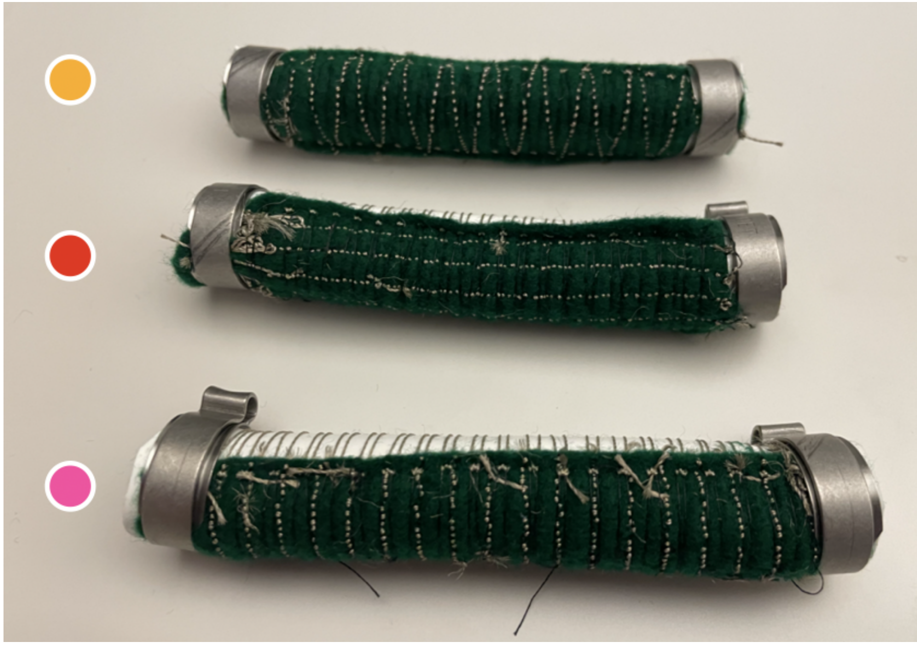


**Figure 13:** Three actuators with embroidery on the backing material and over the tube. The top actuator has criss-cross stitch lines, the middle has horizontal stitch lines, and the bottom has vertical stitch lines. The colors reference Figure 14 below.

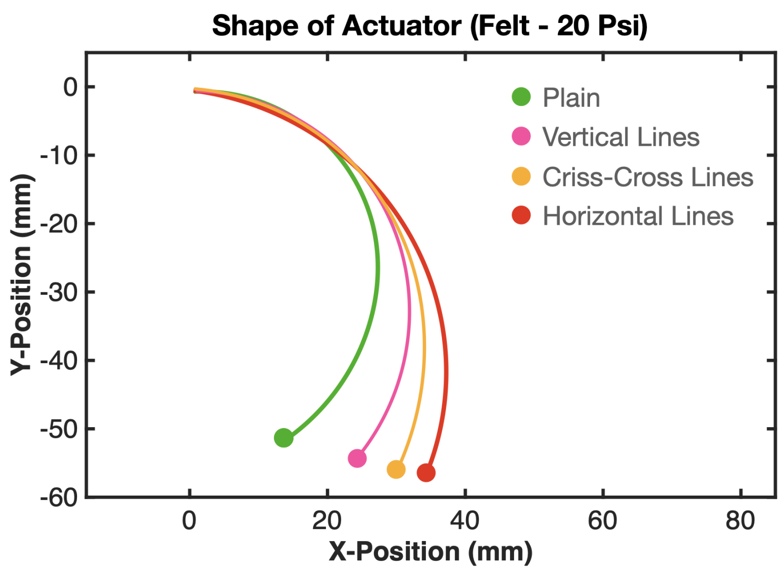



**Figure 14:** The performance of four felt actuators: one with no additional embroidery (green), one with embroidered vertical lines (pink), one with embroidered criss-cross lines (orange), and one with embroidered horizontal line (red). Any additional embroidery on the material backing reduces the actuator curvature.

Adding embroidery to the backing material will be useful as it has the ability to affect the curvature as shown above. The exact embroidery pattern could be planned out based on the type of motion desired. For example, if the motion needs to be greatly restricted then horizontal lines could be added; however, if only a small reduction in curvature is desired, vertical lines could be used. Furthermore, this extra embroidery could be completed in the same manufacturing stage as the embroidery that goes over the top of the tube, maximizing efficiency.

### 5.3 The Effect of Repeated Use

In order to be useful in robotic and wearable applications, the movement of the actuator must be fairly repeatable. Figure 15 shows cycle testing for each embroidery backing: felt, cotton, and polyester. The actuator was pressurized 500 times, and every 50 cycles the position of the end was captured. The change in position from the displacement at cycle 'zero' is shown below. This means polyester traveled 28mm further at the end of 500 cycles than at the beginning. While there were still changes, felt and cotton only traveled 9mm and 5mm further, respectively. Felt and cotton would be better material choices in an application where exact position matters; however, methods to increase accuracy further for all materials should be explored.

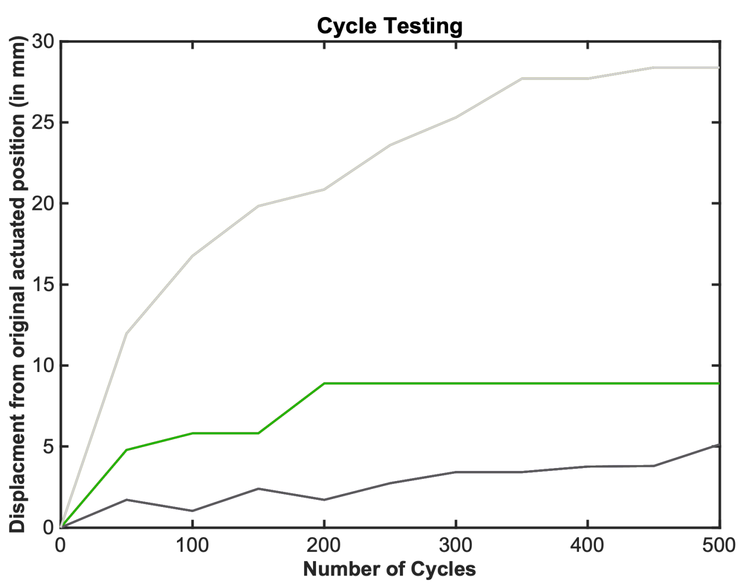



**Figure 15:** Cycle testing results for felt (green), cotton (dark gray), and polyester (light gray) where each actuator was pressurized 500 times and the corresponding change in position compared to the initial actuation was measured.

### 4.4 Failure Modes

While the actuators exhibit strong performance in terms of manufacturability and displacement, it is important to consider the different potential failure modes. The embroidered actuators could be used in wearables and robotics where safety and performance are top priorities. Figure 16 demonstrates three key failure modes that occurred during testing of the actuators.

Failure (a) is a bulge in the inner tube that arose from uneven gaps between the thread on the top surface of the actuator. At low pressure, these gaps do not cause bulging; however, when the pressure is sufficiently high (around 30psi), the inner tube is forced out of the large gaps to create these bulges. They can cause permanent damage to the actuator as the deformation of the inner tube becomes elastic at higher pressures, meaning that they will never return to their original shape. The second failure mode, (b), is a more extreme version of failure (a). If the bulge initially appears and the pressure is high enough, the force on the backing material rips it apart. Failures (a) and (b) could be reduced in frequency by setting a smaller pitch between the top threads to minimize gapping. Additionally, pressures should stay below 30psi.

The final failure, (c), occurs when the acrylic end piece is ejected out of the actuator. This takes place at high pressures (20+ psi) when the internal force on the acrylic end piece overcomes the clamping force. This failure can easily be avoided by ensuring the hose clamps are fully tightened and carefully positioning the acrylic piece so that the house clamp lies slightly closer to the end of the actuator than the acrylic piece.

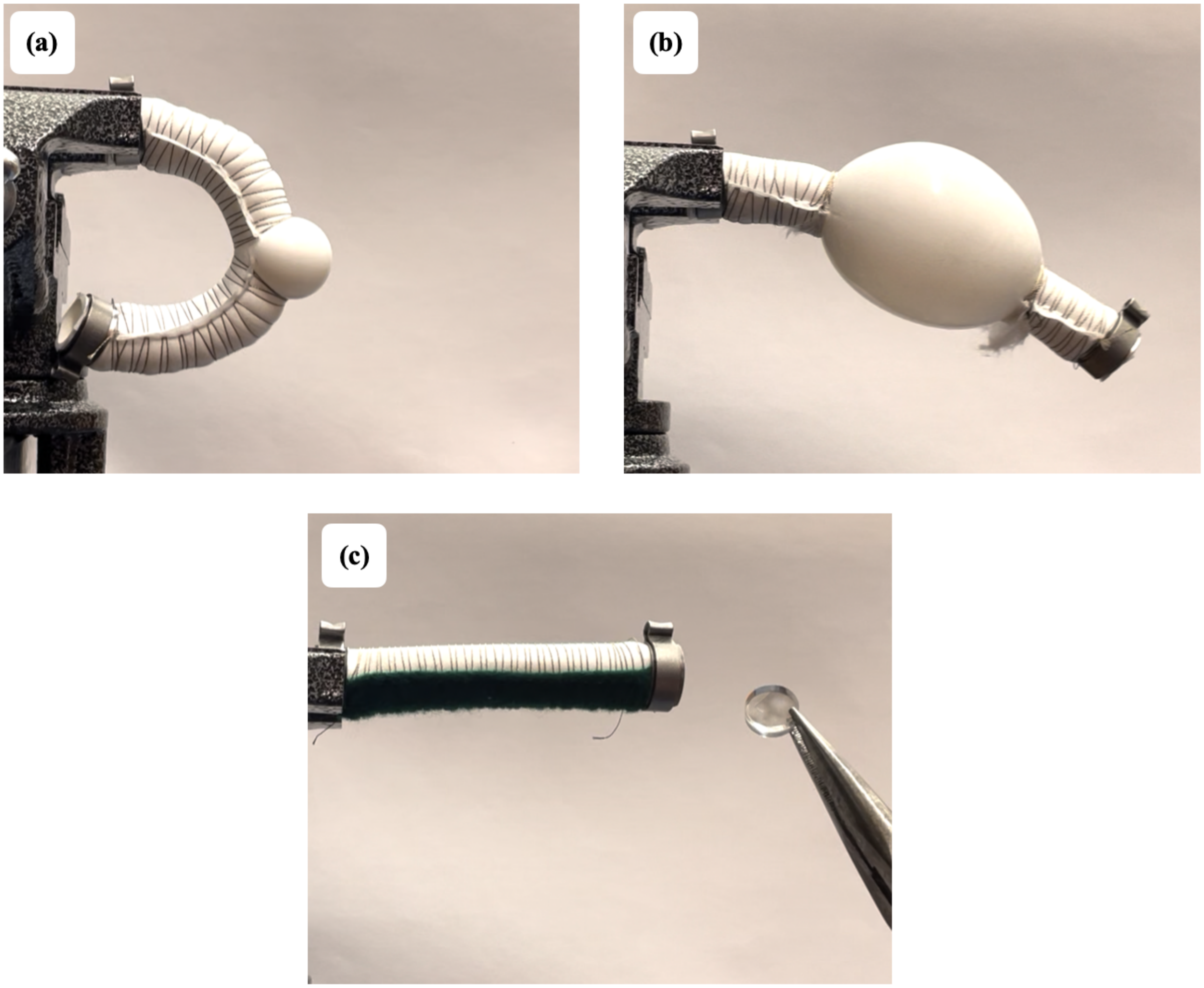



**Figure 16:** Three different failure modes are shown: (a) bulge of the inner tube, (b) ripping of backing material, (c) ejection of end piece. These failures typically occur at high internal pressures and can be avoided through monitoring pressure and greater precision in manufacturing,

# 5. Actuator Applications

### 5.1 Potential Applications

Assistive wearables and soft robotics are two key areas where these actuators could be implemented. [5] The key properties of these actuators that make them useful are their ability to curve under pressure and apply a force through this movement. Furthermore, the amount of curvature can be controlled by varying the pressure applied, material backing, and embroidered pattern on the backing. A soft robotic hand design is explored below; however, other specific applications could include an assistive sleeve to facilitate elbow bending, an assistive glove for gripping objects, and a pneumatic robotic gripper. [5] While the applications are varied, a current limitation is the lack of integrated sensing into the actuators. If sensors were embroidered into the actuator backing, the devices could detect nearby objects and automatically move or grip.

### 5.2 Hand Design

Inspired by the design from Luo et al. (2022), Figure 17 shows a soft robotic hand with five digits made from the embroidered actuators. Each finger has the potential to be individually controlled using a pneumatic valve system that allows specific pressurization for each finger. The components of the hand are simple: five embroidered actuators as fingers, a 3D printed base and cover, and four screws.

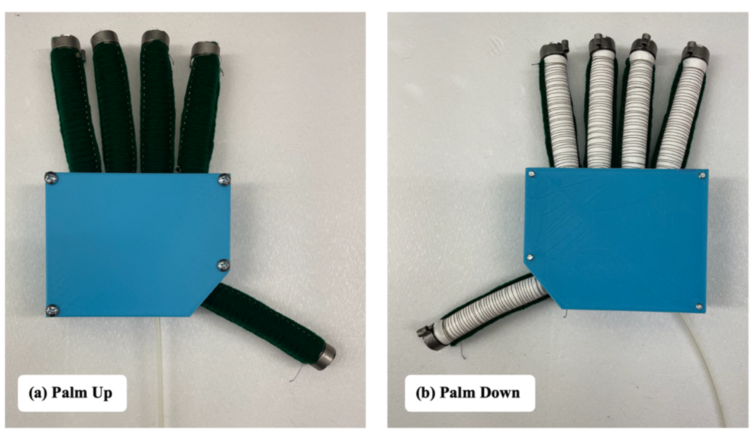



**Figure 17:** A soft robotic hand using embroidered actuators. Each finger can connect to a pneumatic system that allows actuation of the digits. The blue palm is composed of two pieces of 3-D printed plastic, which are secured together using screws.

Figure 18 demonstrates the actuation of an individual finger. From images (a) and (b) it is clear that the actuator moves in a similar way to a human finger. Additionally, as discussed in section 4.1, the higher the internal pressure, the more the finger bends. This type of motion is ideal for gripping objects. Images (c) and (d) demonstrate that the actuation of a single finger can lift the whole palm off the ground. Not only does this point to good gripping ability, but it also shows that the actuators could be used to move a robot in a crawling motion.

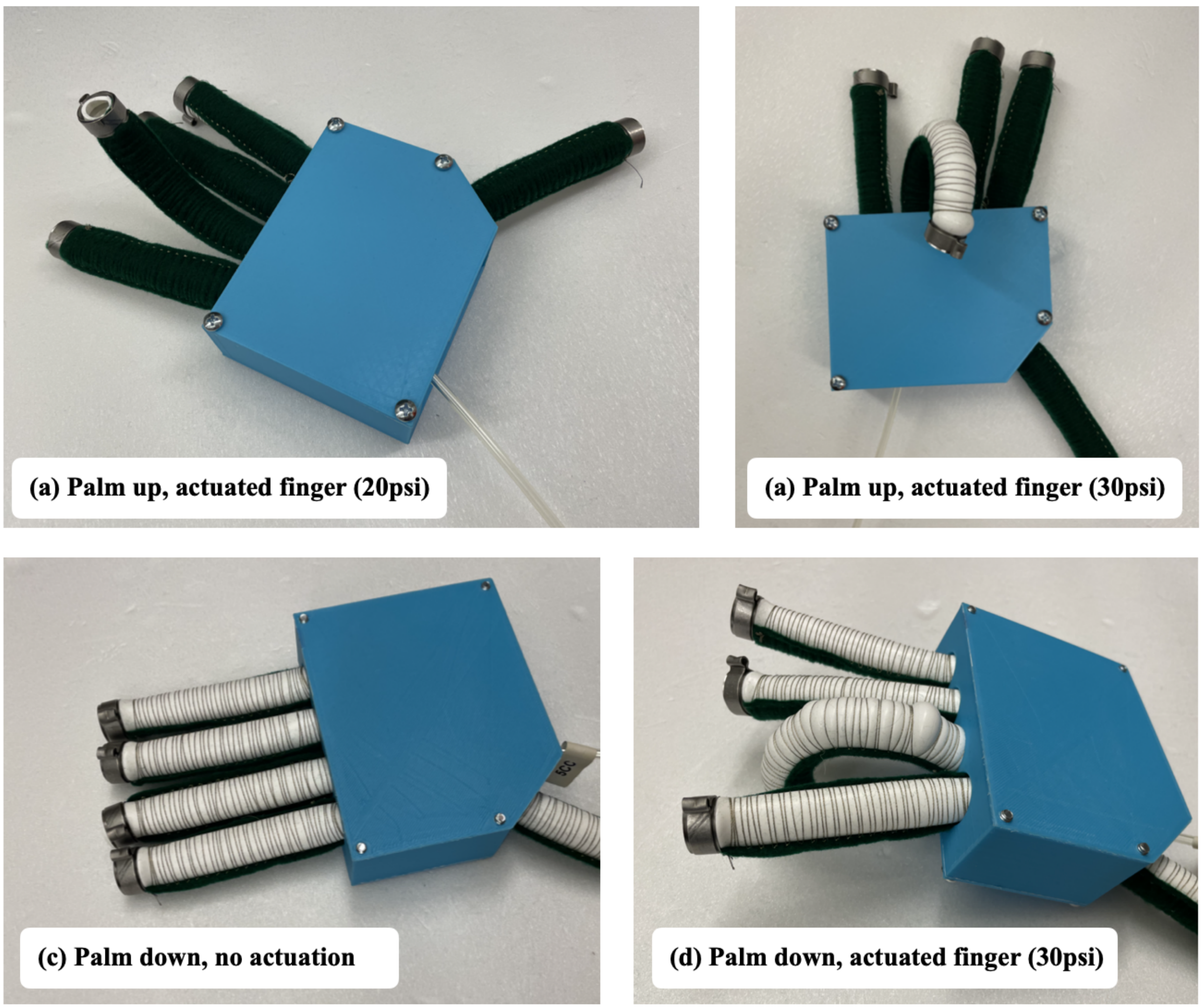



**Figure 18:** The soft robotic hand with an actuated finger. (a) and (b) show the ‘palm up’ behavior at two different pressures, while (c) and (d) demonstrate ‘palm down’ actuation and the hand lifting from the ground.

# 6. Conclusion

### 6.1 Key Conclusions

In this thesis, novel embroidered McKibben actuators were designed and manufactured to improve performance and design flexibility. The manufacturing process remains straightforward and any individual with access to an embroidery machine could assemble them. To begin to characterize these actuators, three different backing materials were investigated, and while no mathematical relationship could be discovered, it was clear that varying the backing material changes the curvature of the actuator at a specific pressure. Furthermore, curvature increases as pressure increases. The performance of the actuators degrades over time; however, either felt or cotton is superior to polyester for more consistent long-term usage. Overall, due to their manufacturability and customizability, these actuators have great potential to be incorporated into wide-ranging soft robotics projects and wearables.

### 6.2 Future Work

Although this thesis explores four important elements of the embroidered actuators – manufacturing process, backing material, additional embroidery, and cycle testing – there is a significant amount of work to be done to thoroughly characterize their performance and increase flexibility. The force exerted by the fingers should be quantified and different types of embroidery thread could be investigated. Additionally, further investigations into how to make the actuators more durable and consistent in cycle testing should be conducted. The most important next step is to integrate the actuators into a variety of robotic systems to examine how their performance could be improved for real world applications.

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