The Design and Manufacturing of Soft Robotic Pneumatic Actuators

Thesis

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By

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ABSTRACT

As technology is advances, people are beginning to see more cybernetic enhancements to compensate for mechanical deficiencies. One area of focus is on bio medics, particularly regarding prosthesis; As the overall health status in the US decreases those needing prosthetic mechanisms increases, due to this, more effective systems should be considered. This is the basis for this research topic: to apply soft robotics pneumatic actuation to a gripper system that closely reflects the mobility and dexterity of the average human being of today.

The important factors considered in the design of an efficient actuator using soft robotic actuation is the efficiency of actuation with pressure, bending angle achieved at certain pressures and optimizations considering different actuator designs and medium transitions for optimizing the finger.

Current implementations of the actuator configuration have been able to reveal major design flaws and critical aspects that would affect the efficiency of the actuator. These proclivities have resulted in an actuator system incapable of producing a force generation profile significant enough to conclude the systems validity, and as such requires more testing and analysis due to issues experienced in the fabrication process.

With the development of a successful actuator design in future work, this project would seek to optimize the systems actuation methods before implementation of sensory encoders or layer jamming systems.

ACKNOWLEDGMENTS

I would like to extend my gratitude to my research advisor and graduate advisors that have supported the preliminary findings in this research and helped to guide and improve upon my research methods throughout the project. With their support this project was made possible. Special thanks to Dr. Haijun Su for permitting me to do my research project, I have been able to expand upon my knowledge of Soft Robotics and compliant mechanisms as a result and this will allow for the continuation of research in this realm as new projects are born from the ideals and methods from this experience.

For the graduate students in the Design and Innovation Simulation Lab, Xianpai Zheng, and George Crowley. Your assistance with methodology from your findings has been instrumental in the developing success of the project and perfection of research methodology as new options and solutions to problems were explored.

Sincere thanks extended to Dr. Hanna Cho for dedicating time to serve as a defense committee member, and for her feedback in my research presentation, and methodology throughout this process since .

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CHAPTER 1: INTRODUCTION

1.1 Soft Robotics

The presence soft robotic mechanisms have had in robotics research have been significant to say the least. These mechanisms are made of deformable materials which allow them to be durable, less likely to damage sensitive payloads, or harm humans during interaction [1][2]. Soft Robots are adaptable and can be lighter weight, less expensive, and more customizable for different applications [3]. There are different actuation configurations that would alter how the mechanisms make use of the advantages and disadvantages of soft robotic actuators, which are factors that could determine the effectiveness of the actuators.

1.2 Advantages and Disadvantages

Soft robotic actuators have become popular throughout the years due to some advantages they offer over most rigid structures such as customizability in different applications, lighter weight, and a lower probability of damaging payloads during interactions [4]. These can benefit the structures by adding a higher degree of adaptability to use cases, making the configurations and methods of fabrication more cost effective and easier to control. There are also added safety benefits allowing these mechanisms to have many more applications with which they can be adapted to. However, there are also significant disadvantages to be considered, such as the mechanisms compliance causing positional accuracy to be sacrificed making it more complex to determine the end effector position and control [5]. Also, considering the actuator softness, a significant deal of resistive force is sacrificed. These disadvantages can however be mitigated by implementation of unique systems and devices to overcome both disadvantages or make them less impactful to the design such as layer jamming systems or joint sensory encoders. Layer jamming is a method used to vary stiffness of an actuation system by applying a compressive (negative) force on sheets of material with a high coefficient of friction otherwise known as the jamming layers through a vacuum sealed medium, this stiffening can lock the mechanism and emulate a rigid body structure enabling resistive forces to be maintained [6]. Sensory Encoders are small devices mounted to mechanical manipulators that sense positional information such as angles of rotation or displacement for prismatic joints [7]. The incorporation of these will provide a strategy for optimization in future work on this thesis topic but will not be the primary objective of this thesis body of work.

1.3 Thesis Objective

The purpose of this thesis is to design and fabricate a prototype of a pneumatic actuator system that better resembles those found in nature taking advantage of benefits of a soft robotic mechanism and mitigating some of its natural deficiencies. The aim in this thesis is to explore the viability of a multi-medium configuration, consider how well it compares to traditional rigid body systems, current unibody soft robotic systems, and seeks to determine best implementations.

1.4 Thesis Overview

This thesis is comprised of five chapters, in chapter one an introduction to the subject topic, the advantages and disadvantages of the system considered, and the objective and overview of the thesis. Chapter two discusses the methodology used which will detail the design inspiration for the actuation system and configuration options, the method of actuation used, fabrication methods considered, material selection for the 3D method and molding, and details on how performance were assessed. Chapter three, four and five detail the design, fabrication, testing and results of each actuator design configuration, changes incorporated and changes through each iteration. Chapter six is the conclusion which providing a summary of the current work and discussing how this project would develop through future work.

CHAPTER 2: METHODOLOGY

This chapter consists of the design motivation considerations and the actuation method used in this project, the method of actuation, fabrication methods considered for each medium, material selection for each fabrication method, and preliminary details of how performance will be assessed.

2.1 Design Motivation

This research project seeks to design and fabricate a prototype of a pneumatic actuator system that better resembles those found in nature, and one of the most common systems found in most macro-organisms are the bone and cartilage systems which usually are actuated by small electrical signals that are transmitted through the nerves to actuate linear muscles. If just the bone and cartilage are considered as shown in Figure 1 below it can be seen that the hand is comprised of several rigid body segments held together by cartilage.

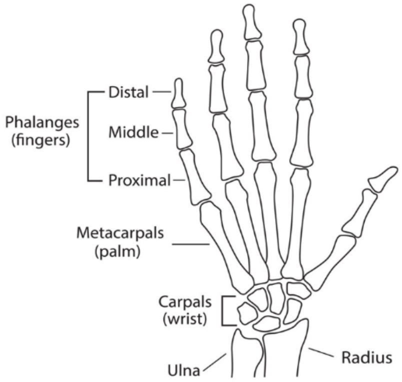

Figure 1: Skeletal hand anatomy [8]

Using a combination of rigid and soft materials a similar configuration can be achieved by a configuration of soft material at the joints and rigid bodies in place of the bone structures between each joint.

The goal is to emulate the human hand structure as accurately as possible so the scale-wise the individual joint-actuator configurations should be no smaller than 3.5 inches, this is the standard size of a human index finger, any smaller there might be some issues with the features being a high enough resolution for 3D printing or molding methods. At the scale this allows for scaling up to 7.5 inches where resolution issues were experienced, however, some dimensions are fixed such as the inlet and outlet sizes for the pressure tubes and fabrication.

2.2 Actuation Method of Actuator

The method of actuation used in this research project is pneumatic actuation which uses compressed air to induce rotation to a constrained soft material shown in Figure 2(a) below.

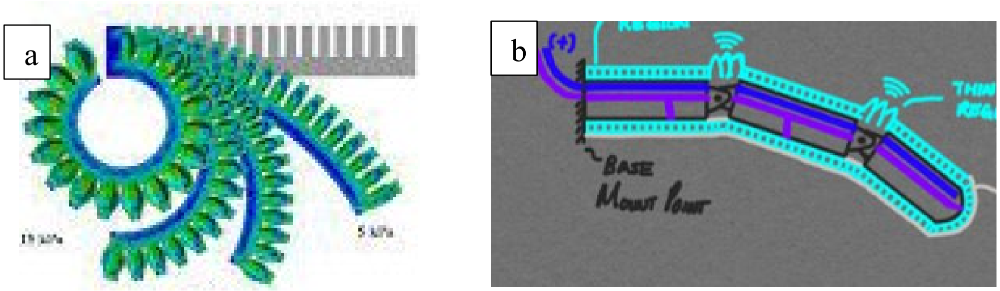

Figure 2: (a) Soft material actuation visualization [4]. (b) The conceptualized multi-medium configuration.

A conceptual sketch was created to visualize how the multi-medium system shown in Figure 2(b) where consideration for both positive and negative air pressure channels were designed in. The positive pressure channel would accommodate for the main actuation which would actuate the bellows shown by the ribbed regions which are above each pin joint between the rigid segments. The negative channels are for considerations of layer jamming or some jamming system which was a method of overcoming the stiffness disadvantage of soft robotic structures, this was for future implementations and would not be as relevant in this phase of the design process.

2.3 Fabrication methods

This section will discuss the considerations of each of the fabrication methods used to create components in the complete actuator configuration.

2.3.1 3D Printed Material

The 3D printer primarily used was the MakerBot Replicator+ for the rigid structures and the silicone molds, this printer had a fabrication resolution upward of 4 millimeters or 0.157 inches. From these limitations desired material properties were considered, as the type of filaments used would affect what the printer settings were set to, as well as the quality of the parts fabricated. Since that can determine the potential applications these properties are shown in table 1 below.

Table 1: Printer settings for each filament and property comparison

	TPU	PETG	PLA
Extruder Temperature [$°C$]	240-260	230-250	180-230
Printing Bed Temperature [$°C$]	40-60	75-90	20-60
Printer Bed Adhesion	Glue	Glue	Glue
Strength	Very Good	Very Good	Medium
Flexibility	Great	Good	Bad

Each design iteration was created on solid works and exported as .stl files to the 3D printer and printed at the adjusted speeds associated with the material being printed. Each print was inspected for defects and modified and reprinted if necessary.

2.3.2 Silicone Molding

Silicone molding is an essential part of this methodology the actuators that were cast using the silicone molding process. This is a process that involved taking both mixtures of the substances A and B pouring into a container which was estimated by weight. The mixture was then degassed by placing it into a vacuum chamber, the degassing should cause the bubbles to surface from the mixture and burst, 4 minutes was the approximate time for each degassing, and longer if necessary or multiple degassing treatments could be applied. This needed to be done timely because each A and B mixture has a cure time and pot life that will affect how well the components bond.

2.4 Material Selection

This section compares the properties of material in each of the fabrication methods to come up with ideal materials to use during fabrication. This will cover important details considered in the selection process.

2.4.1 3D printed Materials

The main consideration for the 3D printed components is for the rigid segments of the finger between each silicone actuator, for this the material needed to have good strength, low deformation for forces that will induce bending in the actuator. For these properties Polylactic acid (PLA) was the best choice of what was provided in the lab. Many of the options available wouldn’t simulate the bone stiffness as well, which was a major deciding factor behind the material choice.

2.4.2 Silicone Molding Materials

Considerations for the cast parts were for high degree of flexibility and strength to be less likely to damage during actuation and generate considerable force for more effective actuation. The preferred method was to test with actuators that started from just below the degree of softness which could be printed using 3D printers and continue to soften the actuator to see how soft the actuator could be made whilst still being effective. However hardest silicone mixture available in the lab was 30A which on the durometer chart (shore hardness scale) as depicted in Figure 3 below.

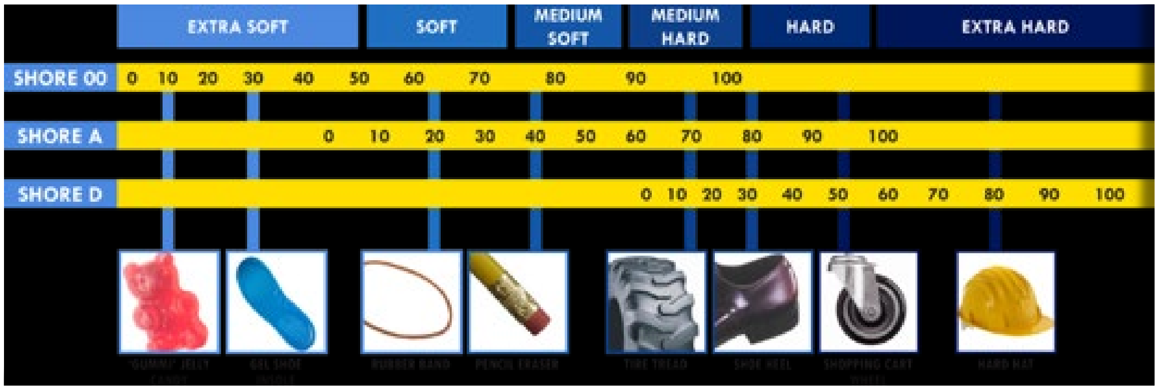

Figure 3: Durometer chart (Shore hardness scale) [9]

After development of design direction, concept designs, and choosing the desired material solid works models could be created and design concepts fabricated to verify concepts and work toward a functional prototype.

CHAPTER 3: ACTUATOR DESIGN CONCEPT 0

This chapter consists of the design, fabrication, and analysis of the actuator design concept 0. Since this actuator design did not make it out of the design phase improvements for future implementations will be discussed after the design details.

3.1 Design

The initial design classified Design Concept 0 consist of a simple three segment finger rigid link structure. This configuration would utilize a single soft actuator that would cover the entire body of the actuator similar to the Figure 2b concept sketch.

The pins were designed to have 0.4-inch pins used to hold the configuration together. Much like the initial sketch this concept shown in Figure 4(b) considers a dual channel actuator with an open line for negative pressure implementations at a later stage in the process.

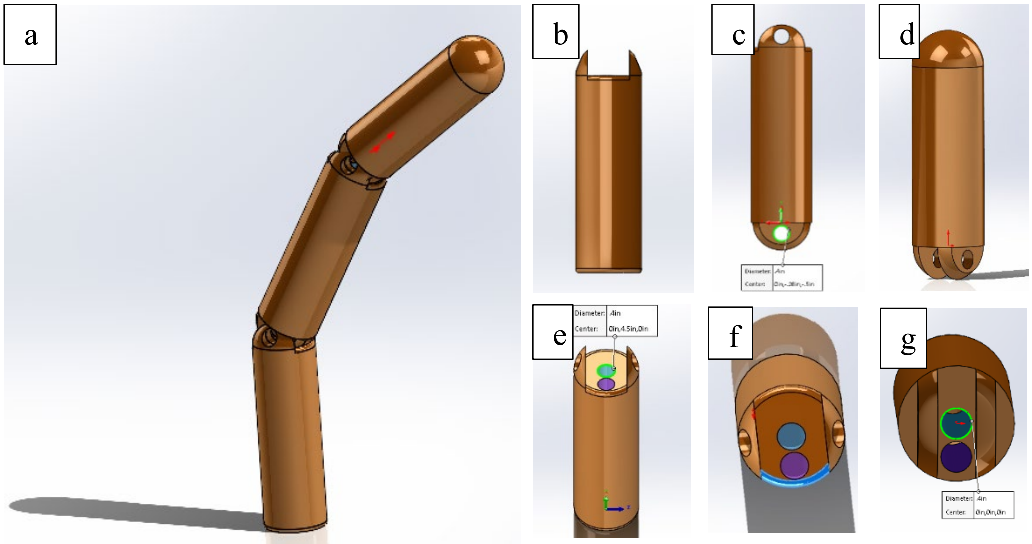

Figure 4: Actuator design concept 0 (a) Complete assembly (b) Base segment, front view (c) Middle segment, front view (d) Tip segment, front view (e) Base segment, isometric view (f) Middle segment, top view (g) Tip segment, bottom view

This design was kept from being fabricated due to some design flaws; first certain sections of the body could not be printed due to the roundness of the body. Even setting a raft under the body with supports, the 3D printer would have to print across an unsupported gap which will cause the print to sag as it cures. If rotating such that the base segment sits flat along the print bed many of the same issues still exist with the mid and top pieces of the finger. Additionally, with both positive and negative pressure channels open it would pose a problem trying to actuate the configuration while both channels function there would need to be a separation between the vacuum layer and the positive pressure layer. There were some considerations for implementing an air pressure channel sleeve that would insert into each of the channels to route the air where it needed to go, but this was ultimately decided against due to the impacts of the errors that would be experienced during printing. Due to this, another concept would need to be considered that would use a different shape of the rigid body segments and focus on positive pressure actuation only for simplicity.

3.2 Analysis

This design was not continued to the next phase due to the complications it would bring during the fabrication process. The rounded edges on this design would pose to much of a problem to try to fabricate each of the segments, a plausible step to take if considered in future work would be to create a flat base in one of the planes to print from and start by focusing on one (positive) actuation channel first. Using the conceptual actuator similar to that represented in Figure 2(b) it is believed that a functional actuator could be realized.

CHAPTER 4: ACTUATOR DESIGN CONCEPT 1

This chapter explores the design, fabrication, testing and analysis of the actuator design concept 1. This was a modified design of the initial design, in which all edges were flattened, and a smaller soft actuation bellow system was implemented just above the pin joints in each segment. This new soft actuator would require less material, covering the inlet/outlet holes of the actuator and clamps were initially implemented as a means to keep the soft actuator in place.

4.1 Design and Fabrication (Rigid Segments)

In this design, much consideration was given to how the body would be 3D printed so there were many changes were made to the body design of the rigid segments. The surfaces were made flat, and clamps were added to lock the soft actuator in place at the mechanism's openings. Early Designs had hollowed the part innards to make it as light as possible, this design is shown in Figure 5.

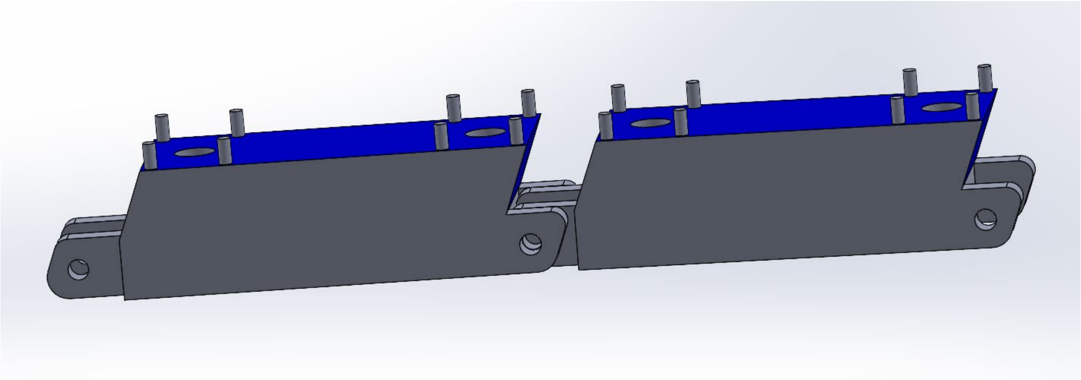

Figure 5: Actuator design concept 1

Fabricating this design revealed many issues with the features in the initial design concept as highlighted by Figure 6.

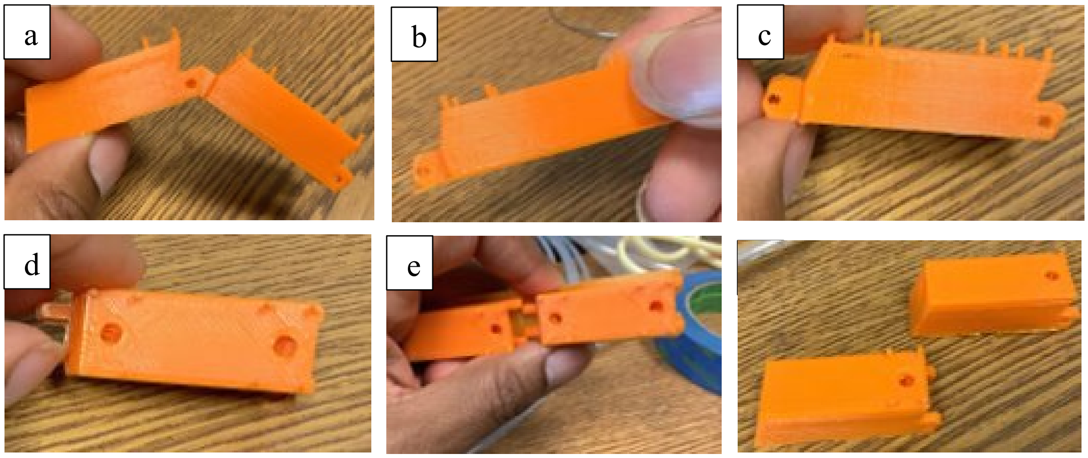

Figure 6: Actuator design concept 1, printing errors (a)Axis of rotation not aligning (b) Pin joint potential failure mode (c) Hollowed wall scorching defect (d) Loose material inside (e) Tolerancing for interlocking components (f) Broken clamps on top right piece.

Due to the design of the pin joint on each segment, there was a point of clash on the body when rotating the holes would become unaligned as shown in Figure 6(a) and seeing how little material was left on the outside of the hole (shown in Figure 6(b)) the location of the hole needed to be moved on the joint as well as a slight lengthening to make sure that when rotating that it can be cleared with the holes still aligning. Hollowing out of the design caused scorching marks during fabrication and loose material to settle inside the body (Figure 6(c) and 6 (d) respectively), the hollowed inside was filled in and the inlet/outlet was lofted to ensure better print quality and performance. There were few tolerancing issues which made it harder to join the segments together (Figure 6(e)), and due to design, certain features like the clamps continued to break and fall off (Figure 6(f)).

The pin holes were initially designed for custom pins, due to how difficult they were to locate the holes were increased from 0.08 inches to 0.12 inches this meant M2 screws, which were more common, could be used. The improved design iteration is depicted in Figure 7 (a), and 7 (b).

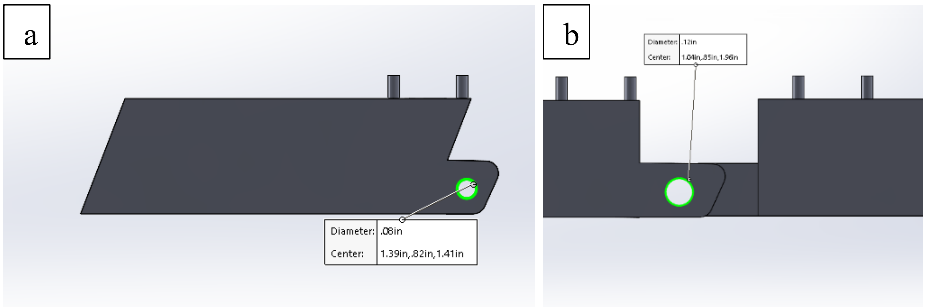

Figure 7: Actuator design concept 1, 1-2 (a) 0.08-inch pin joint hole (b) 0.12-inch pin joint hole

After testing the main components of that designs pressure hole inlet and outlet flow and the pin joints it was realized that due to placement of the inlets the soft actuator would have difficulty actuating because of where it would push against the main body, for actuation testing it would have larger forces to overcome and should be actuated from the middle and instead of using a 3-segment finger for testing a 2-segment test finger would be used. As a result, the finger was lengthened as shown in Figure 8(a) and 8(b).

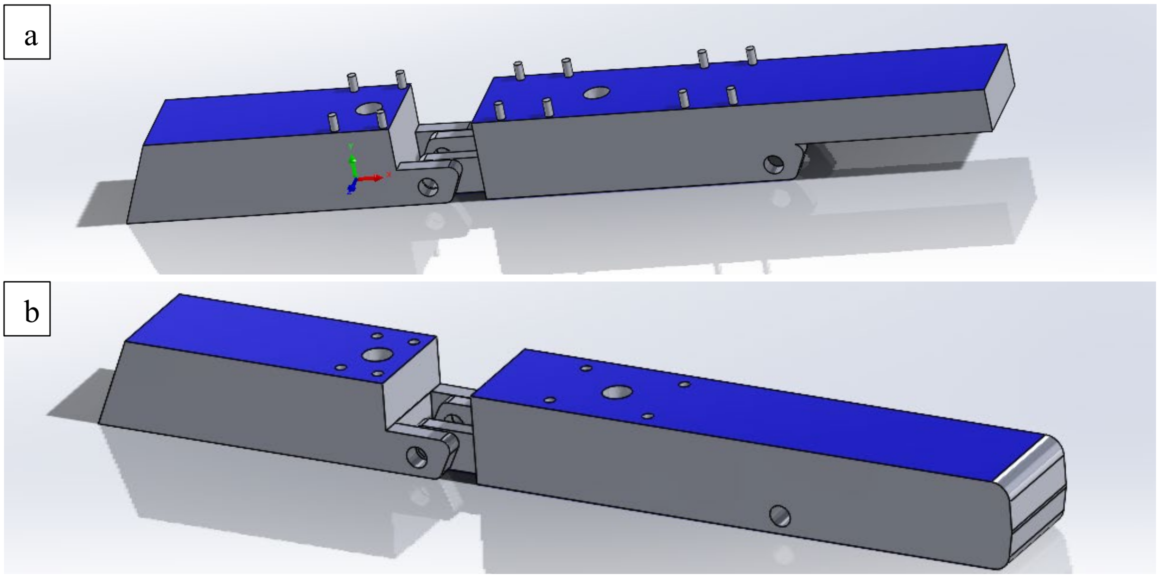

Figure 8: Design direction (a) 2-1, Changed the payload interface (b) 3-1, Inverted clamps

Fabication and testing these new designs would help to decide the payload interface design and if the clamps should be inverted. The printed segments, configuration prototype, and comparisons are shown below (Figure 9).

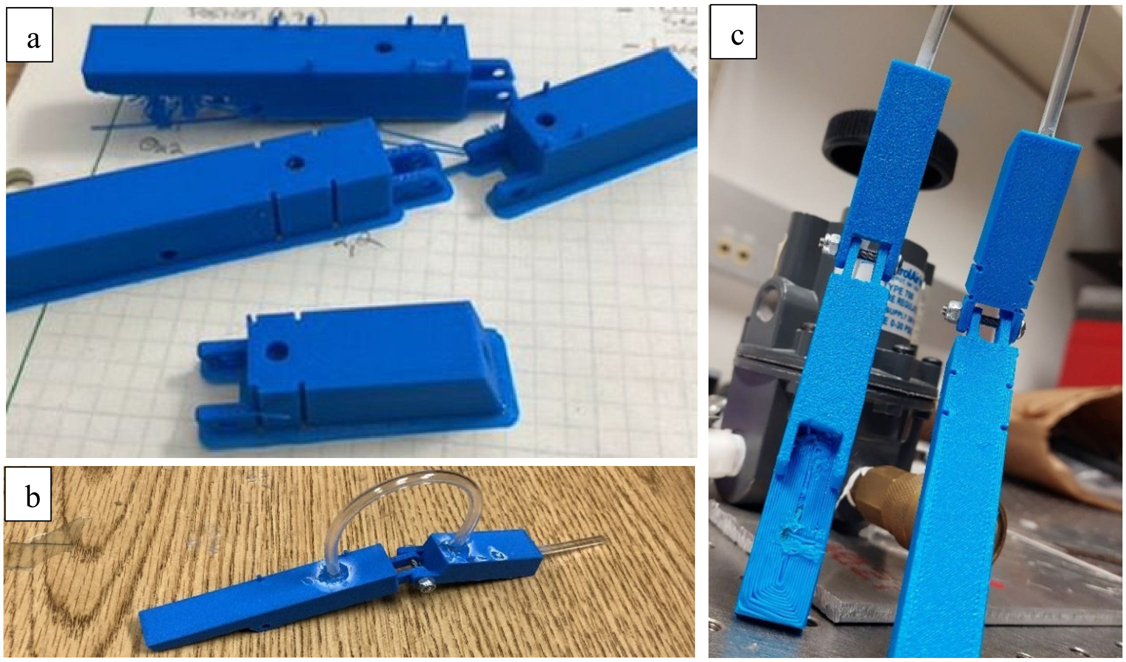

Figure 9: Design direction (a) Component inspection (b) Complete concept prototype (c) Configuration comparison

In Figure 9(a) the components were completed and inspected for defects, upon passing the inspection the prototype was created as shown in Figure 9(b), this was used as a substitute while the soft actuator was being designed and fabricated. During fabrication it was revealed that the 8(a) design had some rough aspects which were shown in the Figure 9(c) comparison. The Figure 8(b) design was selected as the design direction that was pressure and functionally tested as a configuration.

4.2 Testing and Results

This section will cover tests conducted and changes for the actuator system as a result. There were two phases of testing done prior to testing the complete configuration, the functionality of mechanical components and the pressure testing before testing the efficiency of actuation.

4.2.1 Functionality Testing

The functionality of the actuator was tested by either allowing the base segment or the middle segment of the rigid body actuator to be fixed as shown in Figure 10 below and the stiffness of the pin joint was tested and calibrated to make sure it was loose enough to allow joint rotation with low actuation forces.

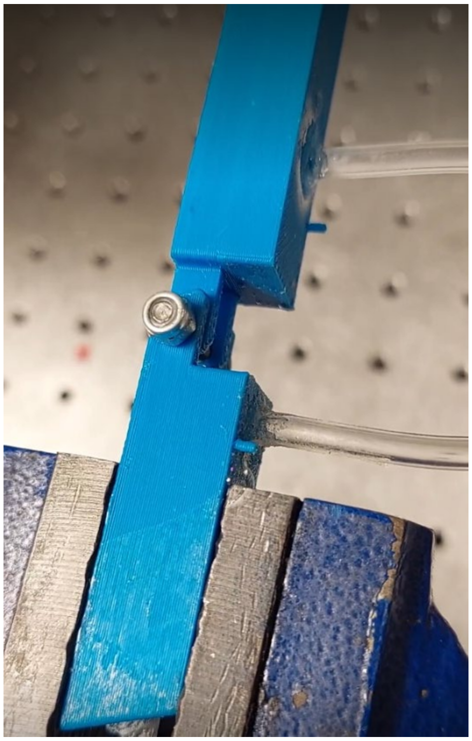

Figure 9: Functional test set up

The actuator was manually tested by bending the non-pressurized system and making adjustments and the pin was very loose and was ready to test for pressure prior to complete configuration testing.

4.2.2 Pressure Testing

The system was pressurized to see how well the system held pressure, for this test it wasn’t essential to keep the ends constrained, the set up was shown in Figure 11. In this test success or failure was dictated based on if pressure leaks could be detected or not.

Figure 10: Pressure testing, leaks detected.

During testing a pressure leak was detected in the system and due to it being difficult to pinpoint the leak, a section of the segment was coated in a substance to reveal where air was leaking out and it was revealed that the entire 3D printed body was leaking air. This was fixed by changing the settings 3D printer to a lower speed to 30 mm/s to allow or more layers of filament on the sidewalls and 4-6 layers on the top and bottom this ensured airtightness between the side walls and the top. After retesting the new segments shows some leaks around where the inverted clamp holes were but seemed to provide a mostly airtight structure. Since these holes would be sealed closed when the real actuator was attached to the configuration this was overlooked.

4.2.3 Actuation Testing

During actuation testing with the prototype soft actuator the goal was just to prove concept viability while the soft actuation system was in development this was done similar to how the real test would be performed. The actuator was fixed at one end in a straight orientation and a force sensor gently aligned such that the fingertip rested on the force sensor slightly, the test set up is displayed in Figure 12 below. Once zeroed out the configuration was pressurized resulting in force being generated against the force sensor which would output a resistive force value. When pressurized the system, managed to generate .08 N max force only regardless of how much more pressure was added to the system.

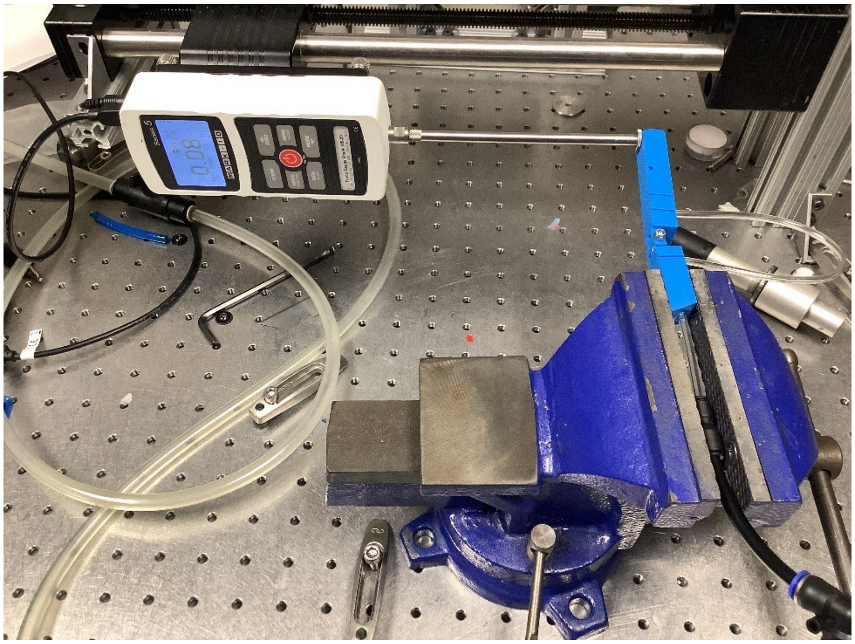

Figure 11: Actuation test set up

This was indicative of significant leaks in the system or a tight pin joint. As such the viability of the concept could not be verified nor could adequate data be collected beyond the fact that the system was not able to exert 2.9 N of force which is equivalent to a mean passive force of exertion of human fingers. Since the system was now sealed (apart from the clamp holes) the working theory was that pressure was leaking though one of the inlets or outlets between each medium. For concept validation the soft actuator bellows would need to be fabricated and tested and more could be concluded about the system.

4.3 Design and Fabrication (Soft Actuator)

For the configuration to be efficient the soft actuator would need to be similarly sealed and flexible so that it can expand radially only. The soft actuator mold was designed to be fabricated using silicone molding methods and was meant to sit on the rigid finger segments and actuate downward when pressurized. The soft actuator bellow was constrained using Polypropylene material and the bellow had a wall thickness of 0.10 inches. The bellow had to be fabricated in a 2-step process to get the shape of the internal channel. This was done by designing three components since the middle would otherwise be unrecoverable once the silicone mixture cured. Consideration was given to a water-soluble material, but the complexity of the fabrication was not plausible under the equipment constraints. A 3D model of the bellow molds is shown in Figure 13 below.

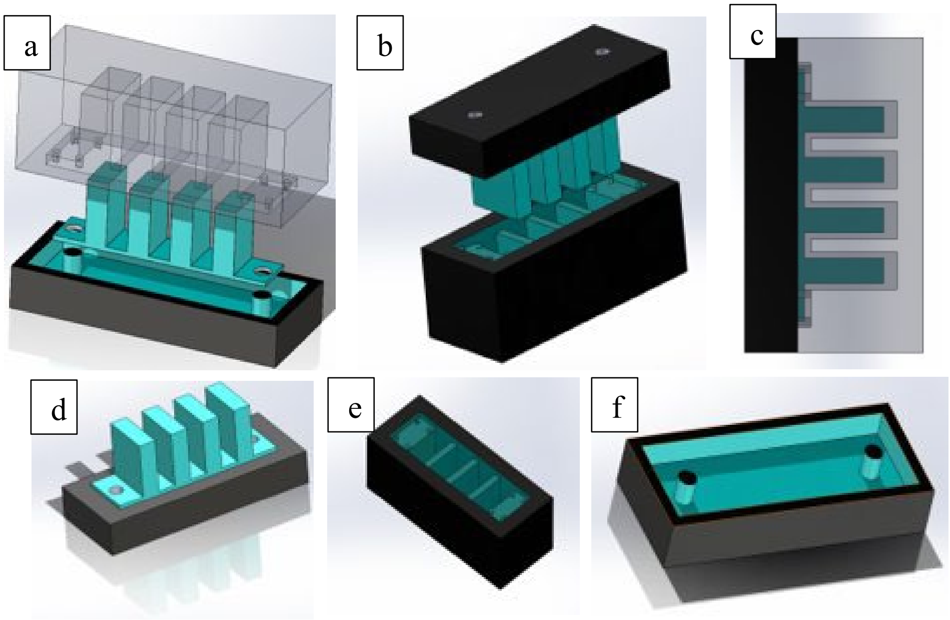

Figure 12: Soft actuator bellow (a) Complete configuration design (b) Upper mold configuration (c) Thickness of top of bellow design (d) Upper bellow mold base part (e) Upper bellow mold top part (f) Lower bellow mold base plate

The soft actuator design was the one depicted in the design models above where the actuator is 1.5 inches in length with a wall thickness of 0.10 inches and 0.15 inches on the top (depicted in Figure 13(c)) to make sure most of the expansion happens in the horizonal direction as opposed to it expanding on the top as well. There were holes implemented in the design (shown in Figure 13(d)) to use injection molding methods of casting to inject the silicone into the part when molding the top half. This method proved ineffective and were later removed, for the traditional method of pouring into the cavity well and pressing the parts together until reaching the stoppers. One thing this design failed at was producing consistently aligned parts due to the stoppers being flat and having no embed features to ensure that the part sits the same way every time (shown in Figure 13(a),(b), and (c) parts).

During fabrication issues were found which resulted in changes for interfaces for the configuration considerations during actuator testing, the three mold casting parts are shown in Figure 14 below.

Figure 13: Bellow molding components (a)Lower base plate (b) Upper inner form (c) Upper outer form

It was found that the top form created did not align with the form in the bottom plate (Figure 14(a)) causing a thickness inconsistency across the top of the soft actuator. The injection molding holes presented in Figure 14(b) did not work as anticipated. Instead, the best practice was to fill the cavity and press the inner form into the cavity until reaching the stopper. The pins that were printed along the inside of the cavity shown in Figure 14(c) for the clamp were not very strong and broke in every iteration fabricated, as a result the clamp idea was removed, and the bellow was to just be glued to the structure until a better solution could be established. The completed bellow ready for testing is shown in Figure 15 below.

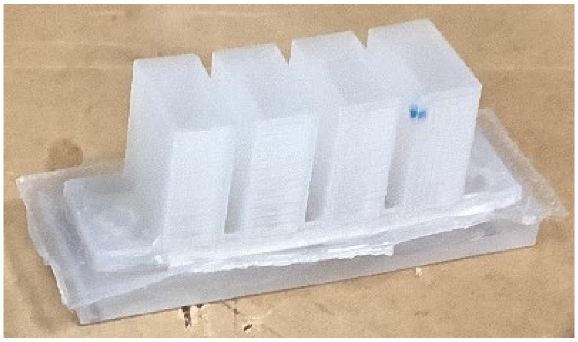

Figure 14: Soft actuator fabricated

The bellow mold casting was visually inspected as it prepared for pressure testing and was deemed a closed system showing no apparent issues apart from the thickness differential across a small area on the top that created a potential failure mode. There was a piece of the clamp pins that got stuck in the mold casting, but this was not anticipated to cause issues during pressure, or actuation testing.

4.4 Testing and results (Soft Actuator)

This section covers the pressure testing set up and results of the silicone actuator. Testing for this system involved holding the body of the soft actuator stationary while pressurizing the system as shown in Figure 16 and observing to verify that the bellows expand and make contact resulting in a rotation.

Figure 16: Pressure test set up for the soft actuator

During testing of the soft actuator, each soft actuator system failed for reasons which weren’t clear until the 3rd-4th test iteration. Common issues and failure modes during testing is shown in Figure 17.

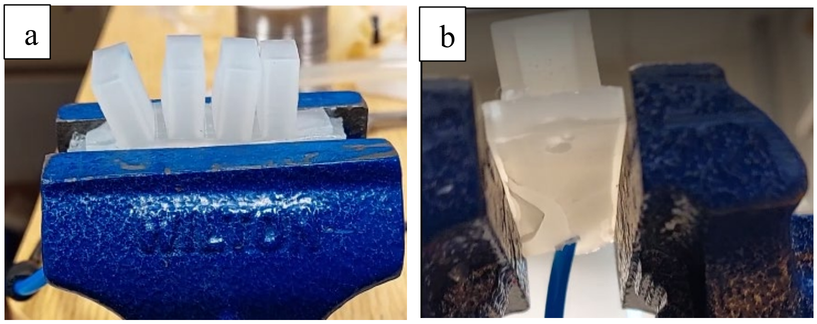

Figure 17: Failure modes (a) Unexpected expansion (b) Bottom layer failure

One testing iteration (not captured) where the soft actuator expanded as anticipated and made contact inducing a rotation, this was an idealized case where no issues were detected but on the second test that was recorded the chamber experienced a failure and expansion happened in the lower chamber similar to Figure 17(a) meaning the air stopped flowing to the upper bellows. This issue could likely be contributed to how the upper and lower forms don’t line up perfectly and there is a small area where the thickness is not the same as the rest of the body. In a test following a different failure was revealed as shown in Figure 17(b) where the area between the soft actuator base and the constrain layer failed, this was a result of more than one issue in the design and fabrication. Fabricating the soft actuation system, the silicone was not bonding to the constrain layer like it would with a fabric, this was allowing air to seep in above and below the constrain layer and pressurize a portion of the system that was never meant to be pressurized causing the bottom layers to fail.

4.5 Analysis

This actuator design concept explored a 3D printable multi-medium design that closely resembles the human bone structure with soft actuator bellows placed in-between. This design had many successes that were carried into future design considerations but also many opportunities for improvement. The design was only capable of producing .08N force which is well below passive force generation for humans if 2.9N. To improve this, consideration to improving the actuation should be considered. First, the bellows, on the soft actuation system, when they contact each other they are not pushing any plate or anything that would induce a rotation. There should be an interface between the bellow side wall and the rigid finger segment which could be done by extending the soft actuator or adding height to the rigid actuator segments. Additionally, the inlet and outlet for the pressure channel will need to be relocated so it does not pass through the constrain layer area causing channel failure at the base. With this change even if the silicone doesn’t bond very well to the constrain layer, so long as it is completely sealed within it should still be able to perform its job without causing a failure in the pressure channel. Though the entire configuration was never tested the inverted clamp holes could be a point of air leaking, so sealing these until a decision is made on a design direction for these in later iterations might be considerable.

CHAPTER 5: ACTUATOR DESIGN CONCEPT 2

This chapter covers details for the design, fabrication, testing and analysis of actuator design concept 2. This design takes a more drastic change of Actuator Design Concept 1 and implements a more familiar soft actuator unibody system. The learning outcomes from the previous design are incorporated into this design in that the bellow regions inlet and outlets are parallel to the constrain layer, also incorporating a direct interface between the soft actuator segments and the rigid body segments. There were a few goals with this design, first was to create a functioning actuator system that the multi-medium design could be compared to. Another goal was to use a proven method and work backward to see how well meshing Design Concept 1 (multi-medium) and 2 (unibody) would mitigate proclivities of either design individually.

5.1 Design and Fabrication (Final, unibody)

The final design explored was a unibody finger which was made completely of Dragon Skin 30A silicone. This was a design revisited due to time constraints and lack of a functional actuator. Conceptually, it was similar to traditional soft robotic applications which removed the multi-medium design and for a single air channel for actuation. The mold form design and its components are depicted below in Figure 18.

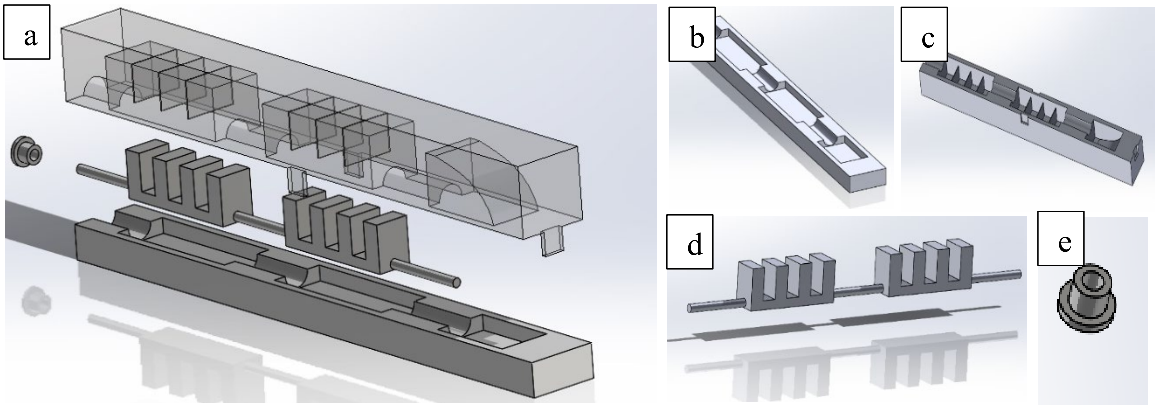

Figure 15: Actuator design concept 2 (a) Full assembly (b) Center form (c) End cap (d) Lower form (e)Upper form

The complete assembly is displayed in Figure 18(a), this design was comprised of the upper and lower forms (Figure 18(b) and 18(c)). Similar to Actuator design concept 1 this was made as a 2-step process using a similar 3-part system structure. The center form depicted in Figure 18(d) is how the internal channel is created. The end cap in Figure 18(e) which was meant to sit on the end of the center form and keep the silicone contents from contained while curing the mold. The thickness of the mold was 0.10 inches but this time the gap between bellows in the actuator portion was much smaller to induce contact much sooner and increase the actuation force. One caveat of the design was that it was not made with the pressure channel extending to the tip of the finger, this design flaw could sacrifice efficiency because it would not have the same grip force as a pressurized actuator. However, these things would be revealed after fabrication and testing of the actuator system.

During fabrication it was realized that unlike previous actuators and mold designs this design due to its small component parts would need to be printed all at once and glue added to the printer bed for better printing otherwise the parts would be prone to not stick to the printer bed and bowl upward. The whole design had a rough finish and due to the tight margins on the end cap it did not work as anticipated while casting the silicone molding as it didn’t slide all the way on to the center form bar, in Figure 19 it can be seen in the left most region how far the center cap would push on to the center cap in relation to the rest of the center form.

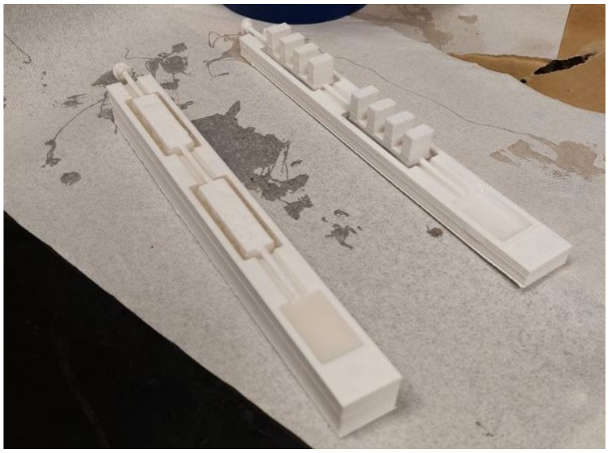

Figure 16: Silicone molding

This created an issue as the end cap was designed to sit flush with the edges of the upper and lower form pieces to keep the silicone material in the mold on both sides. An attempt was made to manually widen the cap hole using hand and power tools, but they ended up breaking the cap and deforming the hole such that it would no longer fit on the center form. This was anticipated to cause problems with the mold casting but could be worked around by using a zip tie or some sort of liquid sealant at the actuator inlet.

All castings using this design had an inherent flaw as a result of the silicone dripping out of the opening during the curing process as shown in Figure 20 below.

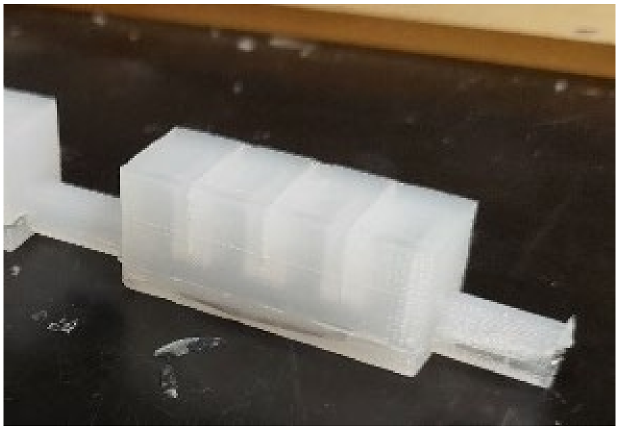

Figure 17: Fabrication error due to material leakage.

During fabrication of the silicone mold the material would leak out of the end with no end cap and issue was created where the inlet was not completely sealed on the sides as depicted in Figure 20. Fortunately, the pressure tubes were just the right size to fit and if pressed in all the way such that the tube outlet breached the inner bellow cavity the risk for pressure to leak out of the actuator inlet was significantly decreased. The distance between the bellows was decreased to induce contact between the bellows sooner, this would induce a higher degree of rotation for a successful system. With few changes to the constrain layer implemented this was ready for complete fabrication inspection then testing.

The full actuator is shown in Figure 21, for a breakdown of all system defects before discussing the testing phase.

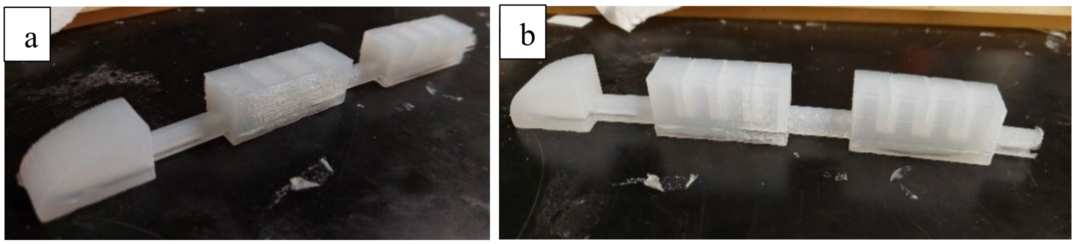

Figure 18: Silicone mold parting line failures (a) Connecting pressure channel (b) Bellow chamber

Apart from the dripping during fabrication, it seemed this design was prone to failing at the separation line where the mold halves meet, this can be seen in three regions along the actuator in Figure 21(a), and 21(b). This could be a result of the upper and lower regions being flat and not designed where an impression would hold the mold halves stationary. The upper and lower form pieces were updated in later iterations to have interlocking tabs that would keep the mold casting in place the due to having realized most failures came the parting line in most iterations, however this was not done intime for final testing, and the best solution for the openings in the mold were to try to patch up the actuator with more material.

5.2 Testing and Results (Final, unibody)

The testing process for this design concept implemented functionality, pressure, and actuation testing all into one due to the actuator being made completely of soft material. The test was done in a similar manner to the pressure tests from before where the actuator was held stationary at the pressure inlet and pressurized to test the actuators bellow contact, the actuator bending, and the ability to hold pressure. A major point of concern was the patch work covering the openings in the actuator, the associated test set up and results from two different orientations were analyzed in Figure 22.

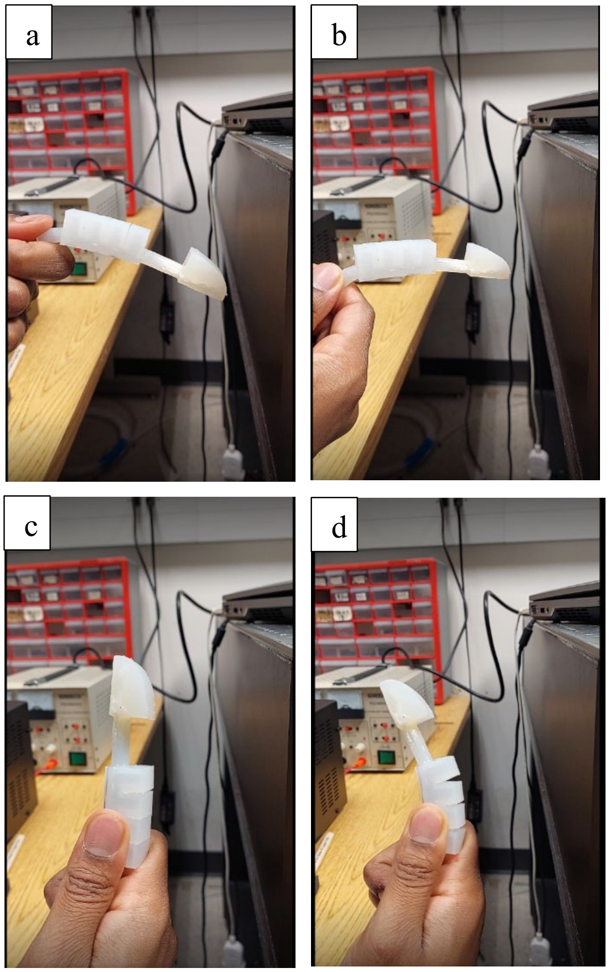

Figure 19: Soft actuator pressure testing bending profile

In both instances the actuator was pressurized to 5-10 psi and the bending profile was observed. The bending shown in the Figure 22(a), and 22(b) was the max achievable, this was likely due to the patchwork meant to reseal the system failing. During testing in this instance, it was noticed that the actuation was much better for the system when one of the failure points at the bottom of the bellow region was covered with an object (a hand after the resealing failed) as shown in Figure 22(c), and 22(d). It can be concluded from this that the degree of bending is a result of the condition of the actuator, and it would be better where the defects from fabrication or conceptualization were improved upon.

5.3 Analysis

This actuator design concept explored a soft actuator unibody design that more closely resembles common soft robotic actuators. This design carried successes of the first modified actuator design concept managing to make some significant improvements on it. A major success of this design is being able to induce bending as the closed system was pressurized, due to the failures that did occur, the system only actuated partially which provides evidence that the system could be improved. Initial improvements to be considered are in molding design to mitigate the openings that the final design had which should improve actuation efficiency, additionally instead of the tip of the actuator not being pressurized it may help with grip force to have a pressurized payload interface. The constrain layer worked much better in this system since it was not in the path of the air pressure and by adapting some elements of the previous actuator design by adding rigid body segments in between the bellow regions this actuator would likely have had the highest force output of all iterations produced during this research project.

CHAPTER 6: CONCLUSION

6.1 Conclusion

Conclusively, it difficult to say certainly whether the multi-medium design would be a viable solution, however coupling that design framework with a unibody silicone molded soft actuator, this configuration shows promise. To improve the quality of the actuator there would need to have some improvements both to the design as well as the mold components. By fixing issues in fabrication a more accurate measure of the design quality can be obtained.

For both multi-medium and unibody systems the soft actuator mold components could benefit from a redesign in the upper and lower forms and how they join. A unique form at the interface that will hold the halves in a specific position/orientation should mitigate the failure mode issues experienced at separation lines and create more consistent soft actuators capable of consistently producing the same results. From here individual issues can be addressed, the multi-medium designs main issues stemmed from the air pressure not effectively travelling through the mediums enough to activate the bellow expansion and getting a point of contact for the bellows and the rigid body structure to induce effective rotation. The main design issues with the soft actuator involve the center form end cap not helping to create an effective inlet, parting line failures and the payload interface (at the fingertip) is not very strong or controllable by changing the air pressure. By focusing more on the design issues and maybe even detecting them sooner, a more effective actuation system could be created with more conclusive results.

Some of the projects most prominent challenges were the level of precision in the 3D printed parts from the lab as well as design issues trying to fabricate completely airtight structures that were effective in actuation.

For the equipment, the desktop printers struggled with small features and either larger scaled designs or more precise printers would be necessary. In discussion with the machine shop, this can be achieved with their equipment, but some design tweaks would need to be made to the molding cavities and the center form pieces for them to be ready for machine shop printing. Ideal methods would be either polyjet or CNC printed methods. These methods will improve the finish allowing for less prominent defects in mold casting and less surface roughness which improve the quality of the prints, decrease likelihood of material bonding to the mold cavity and improved actuation. Other minor improvements during fabrication would involve smaller pouring containers and more careful pouring to prevent bubbles in the mold and a better reinforcement layer consideration to make it less likely that air seeps through the mold, preferably a inelastic cloth material so that the silicone will bond to the material. If air does manage to seep in it doesn’t cause it to fail when pressurized. The current equipment used seems to have some problems producing smooth surfaced moldings, and this impacted the performance during testing.

6.2 Future Work

In future work using what was learned during this project life span, the actuator can be refabricated, and a complete configuration tested for a characterization of how well it generates resistive forces as well as its bending angle while pressurized. Due to the limitations of the equipment, it might also be considerable to refabricate old bellow designs and 3D fingers and see how well they perform as well, varying size and fabrication methods.

The new configurations will consider feedback from the machine shop on how to produce more precise molding parts using polyJet fabrication methods and CNC milling operations. For

CNC milling operations even the improved molding designs would need design tweaks to make smoother outer edges. This is because during milling the edges of the molds created would be too sharp to create with the rounded tool and almost impossible to make. Since these are negligible features to the actuator or its functionality these can be accommodated with no concern to the actuator performance.

With a newly created actuators from each new method and one using scaled-up designs from the old methods, these can be tested against each other to validate the efficiency difference. With that it can be determined if it is worth it to outsource this fabrication, with consideration to cost of manufacturing.

For a working actuation system, implementation of sensory encoders and jamming systems can be considered to improve the quality of actuation and allow for positional accuracy tracking. Finally, a complete hand with 4-fingers and a customized thumb design will be made and a functionality test of the complete configuration can be further tested and optimized.

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