8-2019

Analyzing the Coiling Motion of Plant-Inspired Soft Actuators with Tilted Helix Fiber Reinforcement

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ANALYZING THE COILING MOTION OF PLANT-INSPIRED SOFT ACTUATORS
WITH TILTED HELIX FIBER REINFORCEMENT

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Mechanical Engineering

by
Ryan Kirby Geer
August 2019

Accepted by:
Dr. Suyi Li, Committee Chair
Dr. Ian Walker
Dr. Lonny Thompson
ABSTRACT

Plants have unorthodox motion. The seed appendage of Stork’s Bill plant (Erodium Gruinum) moves in such a way due to two physiological features. Plant cells are reinforced by cellulose fibers distributed in a tilted helix pattern — helixes that are tilted at a certain angle with respect to the longitudinal axis of the cell. Another feature is dehydration of cell tissue which causes volumetric shrinking. Due to the cellulose-fibers and dehydration of cell tissue, the seed appendage can coil and uncoil via a combination of twisting and bending. Coiling motion can be quite useful for robotic manipulation and locomotion purposes. This research proposes and investigates a novel actuator that is inspired and derived from the unique cell wall architecture in the seed appendage of Stork’s Bill plant (Erodium Gruinum). This study aims to examine the coiling and uncoiling motion of a soft pneumatic actuator reinforced with tilted helix fibers. Detailed design and fabrication processes are developed to create a fully functional soft actuator which represents the experimental model. Since the material is “soft”, hyperelastic models are used and compared to the nominal stress-strain data from the uniaxial test to determine which material model best represents the material and used for the FEA model. With both FEA and experimental models created, the setup of both models is developed to gather data for results. From the results, the standard and tilted helix fiber reinforcements show different actuator motion as a tilted helix actuator primarily produce bending in addition to twisting, thus producing coiling. Quantitatively, the FEA and experimental are not in agreement. However, qualitatively, both models show similar coiling motion. Parametric studies are performed by changing the tilt angle of the fiber to show the effectiveness of coiling. The
FEA models are validated qualitatively by the experimental models. In conclusion, larger tilt angles produce more bending motion, thus less twisting motion is shown which causes the actuator to primarily coil outward than produce coils. Lower tilt angles produce less bending motion, thus more twisting motion is shown which causes the actuator to primarily coil more frequently and coil outward to a lesser extent. The results coincide with the study, as soft actuators with a tilted helix fiber reinforcement can primarily produce bending in addition to twisting which results in the coiling motion. With these results, a new family of soft actuators with unique motion can be explored and developed, which is appealing for soft robot application.
DEDICATION

I dedicate this thesis to my family, my Clemson Family, and God.
ACKNOWLEDGMENTS

I would like to thank my advisory committee chair, Dr. Suyi Li, for giving me the opportunity to be his graduate student and helping me along the way over the last few years. I would like to thank Dr. Suyi Li for the guidance he has given me as it has helped me grow in many aspects such as professional etiquette and diligent research. This has truly helped me grow not only as a researcher but as a person. I would also like to thank my advisory committee members: Dr. Lonny Thompson and Dr. Ian Walker. Thanks for answering my questions, guiding me towards the right path, and being a part of my advisory committee.

I would like to thank my Clemson Graduate Mechanical Engineering lab mates of Fluor Daniel EIB 256. Specifically speaking, lab mates from January 2017 to July 2019. Thanks for helping and providing great feedback for research and course questions. I would like to thank Clemson Mechanical Engineering Graduate Department for providing me with a graduate financial assistantship throughout my years Clemson and providing moral support.

Finally, I would like to thank my parents and God most importantly for all that they have done for me to get to this point. I needed their help every step of the way.

Much Love!
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CHAPTER ONE

INTRODUCTION

1.1 Research Objective

Our research objective is to examine the coiling and uncoiling motion of a soft pneumatic actuator reinforced with tilted helix fibers. The soft actuator design will be based on the Erodium Cicutarium (Figure 1.1). Instead of the hygroscopic shrinking and swelling a plant’s tissue goes through to actuate the plant’s motion, the soft actuators will be actuated by pneumatic means due to how quick the process is. Similar to the cell wall and the cellulose fibers that are a part of the Erodium Cicutarium, flexible hyperelastic materials will be used for the cell wall and strong thread for the cellulose fibers [1]. The fibers will serve as the reinforcement for the soft actuator. The primary focus of this research is to identify the effect that a tilted helix fiber reinforcement has on a soft actuator modeled after the cell wall of the Erodium Cicutarium and potentially lead to the coiling of the soft actuators. Also, the soft actuator must have a similar physiological structure like the Erodium Cicutarium. Certain soft actuators have been developed with a strain limiting layer on one side of the soft actuator or multiple pressurized air chambers [2]. This will induce coiling, but it does not have the same physiological features as a plant, thus, it is not assisting in understanding plant’s motion. This is the reason why the soft actuator for this research will be plant driven, especially when it comes to its design. Before the design and fabrication processes for the soft actuators, there is one question that must be asked and answered: What role does the tilt angle play for the soft actuator’s motion?
1.2 Literature Review

To fully understand the influence that soft robots will have on robotics in general, a more detailed look is needed for how the mechanics and physiology of plants can help fabricate and understand a plant-inspired fiber reinforced soft actuator. Also, emphasis will be driven towards understanding the term “soft”, meaning examining the material characteristics of a soft robot along with material models. Once these details have been established, methods of how to fabricate the soft robots will be established. Finally, an observation is made with soft robots that have already been constructed that resembles what the scope of this thesis is. From this observation, conclusions can be drawn about the behavior of soft robots when actuated. With the prior knowledge about plants, soft materials, fabrication of soft robots, and soft robot behavior, a basis for the focus of this research is constructed.
1.2.1 Background in Plant Motion

Soft robots are influenced by animals and plants. However, not many designs of soft robots are plant driven. This means that there is a vast amount of knowledge that can be gathered from plants. For plants such as the Erodium Gruinum (Stork’s Bill), This plant consists of five unique dispersal units [1,3]. Along with each dispersal unit, there is a long thin membrane that will contract to form helixes, the awn. Within the awn are long thin cell tissues. Based on the cell tissues are moist are dry will determine how the plant will behave. When the cell tissues are moist, the tissues will resemble a straight rod. This will cause no change in the plant. However, when the cell tissue is dry, the tissue begins to contract, refer to Figure 1.1. With the contraction, the plant will form a helix. Thus, the plant drills into the soil to disperse the seed [1,4,5]. This helix is formed due to the cellulose fibers being wrapped around the cell wall and hygroscopic shrinking of the plant. The cellulose fibers have a tilted helix structure. The scope of this thesis is based on these principles.

1.2.2 Background in Soft and Rigid Robotics

Soft robotics is an innovative concept and is considered the next major evolution in the field of robotics. The fact that soft robot bodies can be composed of flexible and soft materials, means that complex motion can be generated. In most cases, the complex motion of soft robots can be generated by hydraulic and/or pneumatic means. Unlike soft robots, rigid robots are restricted to a few degrees of freedom due to how dense and rigid these
robots are [6]. Rigid robots are restricted to translation and rotational motions. This is not to say that rigid robots cannot achieve complex motions by combining translational and rotational motions together as done by soft robots. However, to achieve the complex motions for the rigid robots will require a complex design for such applications such as wrapping an arm around an object. Soft robot’s designs are simpler than rigid robot designs as soft robots are capable of complex motions such as elongation, bending, and twisting [7-10].

Meaning that soft robots are capable of a larger variety of tasks and applications that can be completed compared to rigid robots. Applications could include a soft robot hand [11]. A soft robot hand can use its flexibility to easily wrap around an object. Another application includes patient rehabilitation [12-14]. A patient with back pain due to bad posture will be able to have his/her back straightened due to soft robot wrapping and providing reinforcement to the body [15]. Another promising application is that the soft robot can behave as a space probe. For example, if information is needed about the soil or properties of a planet then the space probe will assist A soft robot can be used as a plant and burrow its way into the ground. As the robot burrows its way into the ground, the robot can dispense an object into the ground to record data. Another action could include the soft robot being used as roots and stretch its way throughout the soil. Sensors can be attached to the soft robots to gather data. An advantageous detail about these robots is the fact that they are “soft”. Soft robot’s soft and flexible body will have a less chance of injuring a human than a rigid robot’s strong body. The inherent compliance of the soft robot’s body will allow the interaction between human and robot to be safe. To fully understand the
possible directions soft robots will go in the future, it is imperative to learn as much as possible from the previous experiences.

1.2.3 Background in Hyperelastic Materials

To achieve the flexible, elastic and compliant material used for a soft robot, hyperelastic materials must be used. Hyperelastic materials are elastic in high deformation regions. The deformation and load have a nonlinear relationship. In a real sense, these materials are rubber-like materials. With the hyperelastic material used, there must be appropriate representation for the material, which is where hyperelastic models come into play. There are many hyperelastic models such as Neo-Hookean, Mooney-Rivlin, Ogden, Yeoh, Gent, Van Der Waals, and many more. Research papers have been written about hyperelastic models. However, it is essential to refer to a paper that will tell difference in using some hyperelastic models. A comparison between the Neo-Hookean, Mooney-Rivlin, and Ogden models is made [16]. For each hyperelastic model, there is an associated strain energy density function which can be written in the form of an equation. Also, associated with each model is the Cauchy-Green Deformation tensor. The material properties for a model can be derived from deformation tensor.

Neo-Hookean model is similar to Hooke’s law. Just like in Hooke’s law, where the deformation is small, the stress-strain relationship is linear and can be solved, the Neo-Hookean model will identify the nonlinear stress-strain relationship for large deformation. Associated with the Neo-Hookean model, is the first invariant of the Cauchy-Green Deformation tensor and a one material constant. Mooney Rivlin model is similar to the
Neo-Hookean model with the exception of the number of material constants and the invariants. Mooney Rivlin has two material constants and two invariants from the Cauchy-Green Deformation tensor. This would seem that Mooney Rivlin is a little more accurate in representing a material compared to the Neo-Hookean Model. Ogden has several models based on the order of the strain energy density function. There are two empirical material constants. Unlike the use of invariants for both Neo-Hookean and Mooney Rivlin models, the principal stretch ratios (eigenvalues) from the Cauchy-Green Deformation tensor are used for the Ogden model. Through numerous testing methods, there are some limitations placed on Neo-Hookean and Mooney-Rivlin models when the material has large deformations. However, the limitations are not as prevalent in the Ogden model as it works well with large deformation. Through these conclusions, this information will help shape what and how each material model should be used.

1.2.4 Background in Design and Fabrication Background

For soft fiber-reinforced bending actuators, the fabrication process frequently uses molds [17]. The molding process makes the production time of the soft robots faster and makes grants the ability to create robust design possible. Also, the molding process allows soft robots to be constructed quite frequently. Molds for these soft robots are 3D printed. There is a total of two sets of 3D printed molds that are used to make the soft robots. The first 3D printed mold set will place the indentation for the placement of the fibers. The second 3D printed mold set encapsulates the fibers. When it comes to the design of some fiber reinforced bending soft actuators, a Finite Element Model (FEA) model provides a
realistic response compared to an analytical model [18]. An advantage of using an FEA model compared to the analytical model is that certain parameters can be measured and visualized. Parameters include deformation, stress, strain, among other parameters. For FEA models, the type of mesh must be determined. A mesh is given for a soft fiber-reinforced bending actuator and the fiber reinforcement. For the scale of the soft actuators, the reinforcing fibers are thin, the fibers are treated as a wire with no volume. These details can be used to generate experimental and FEA models to gather data.

1.2.5 Background in Soft robot behavior

The soft robots that have been developed have proven that certain motions are possible such as expansion, elongation, and twisting [19]. In most cases, these soft robots can only perform one of these motions. Fortunately, with multiple soft robots joined together, these soft robots can have complex movements. These advanced and complex movements allow soft robots to complete difficult functions. A hypothetical example, a soft robot is tasked with retrieving a jar. Since the soft robot is composed of different segments of smaller soft robots used for one function, the soft robot will be able to elongate towards its target until the expansion segment of the robot is in the jar. Once the robot reaches this point, the expansion segment can expand until it fills all the space in the jar. This is just one other way to achieve a certain motion.

Another way is to include some sort of strain limiting layer or sleeve [17]. In the case of the strain limiting layer, one side of the actuator has its layer and when pressurized the actuator will bend on this side. For the case with the sleeve, the soft actuators can be
separated into three sections: top, middle, and bottom [20]. Sleeves are added to the top and bottom sections, which will constrict these sections with the middle section exposed. This will cause the soft actuator to achieve bending. The understanding of a soft robot’s movement allows a hypothesis to be made about how a soft actuator will behave when pressurized.

1.3 Thesis Outline

Chapter 2 of the thesis features the design and fabrication of the soft actuator. This will include detail about what is a tilted helix. The design of the soft actuator and mold has the dimensions, size, and design concerns. Also, it will include a detailed list of steps to follow to create a soft actuator. Chapter 3 explores what material models are needed for a “soft” actuator. Hyperelastic models are chosen, and material testing backs the choice of the material model. Chapter 4 has the FEA setup for the FEA simulation. Also, how to set up and conduct the experiment is given.

Data comparison are represented in Chapter 5 and Chapter 6. Chapter 5 has the results from both FEA and experimental models for a soft actuator with tilted helix fiber reinforcement. For the FEA simulation, verification of the chosen mesh along with quantitative data gathered from the nodal positioning from the model. Exclusively, the FEA model is used to compare the soft actuator with a standard helix and tilted helix fiber reinforcement. Finally, experimental data will be compared to the FEA data. Chapter 6 features how changing the tilt angle will influence the actuator. Shape predictions of the actuator with a changing tilt angle and pressure will be introduced for better understanding.
Finally, chapter 7 summarizes conclusions from the results and what the future holds for this research.
CHAPTER TWO

ACTUATOR DESIGN AND FABRICATION

The following mold fabrication and design processes are inspired by the [21].

2.1 Tilted Helix

One of the primary concerns about the soft actuators, in general, is the design. The soft actuator will be modeled after a cylindrical hollow tube capped at both ends, in other words, a cylindrical tube with a cylindrical cavity in the center. Associated with the cylindrical tube will be the fiber reinforcement. The reinforcement normally has a standard helix structure. However, for this research, the reinforcement has the tilted helix shape and an associated tilt angle. A tilted helix is a helix that is tilted at a certain angle with respect to its longitudinal axis. This certain angle is also referred to as the tilt angle. The difference between the tilted helix and a standard helix is represented by Figure 2.1 [22].
Equations of the standard helix are given by equation (1) to equation (3) with respect to the XYZ axes respectively. The symbol $r$ represents the radius of the helix, while $p$, and represents the pitch of the helix or spacing between loops. It is important to note what is the radius of your helix is. The radius of the helix is the sum of the inner surface radius and the inner layer thickness. The inner layer thickness will be explained in a later section. Axis XYZ represents the horizontal direction, depth direction, and the vertical direction respectively.

\begin{align*}
x &= r \cos t \\
y &= r \sin t \\
z &= \frac{p}{2\pi} t
\end{align*}

Figure 2.1: Standard and tilted helix
For a visual representation of a standard helix, Figure 2.2 is given.

*Figure 2.2: Standard helix fiber reinforcement*

The only difference between the standard and tilted helix is the equation for the $Z$-axis equation (equation (3)). The $Z$-axis equation for the tilted helix is represented by equation (4).

\[
z = \frac{p}{2\pi} t + A \cos t
\]  

(4)

The product of the trigonometric function and parameter $A$ is what causes the tilted helix. Parameter $A$ can also be known as the tilt parameter. Due to the tilt angle being the controlled value, the tilt parameter can be solved for using equation (5), where $\alpha$ is the tilt angle. The tilt parameter, $A$, is solely dependent on the radius of the helix, $r$, and the tilt angle $\alpha$ [23].

\[
A = r \tan \alpha
\]  

(5)
With this knowledge of how to formulate the tilted helix (Figure 2.3), a mold can be designed to incorporate a tilted helix fiber. Thus, a geometry design for the soft actuator can be solved.

Figure 2.3: Tilted helix fiber reinforcement

2.2 Geometry Design

What shape the soft actuator is modeled after is of importance. The design of traditional fiber reinforced soft actuator is inspired by pneumatic artificial muscles (PAM) or McKibben actuators and fluidic flexible matrix composites (F^2MC) [24-26]. Since the helixes are modeled after a circular shape, the soft actuator’s body will be modeled after a
cylindrical tube with a cylindrical cavity in the center. Initially, the total length of the actuator’s body was chosen to be around six to seven inches as these represent the previous actuator designs. However, fabricating the actuators with this length created difficulties due to observing how much coiling occurs when the soft actuator is pressurized. More details of the old actuator are given by Appendix A. The soft actuator was tested at greater lengths through FEA simulations to clearly observe how much the coiling is present.

The length of the soft actuator was chosen to be 339 mm. The reason for this is to make the fiber coverage of the actuator be 305 mm (12 inches). Extra material is added to the ends of the soft actuator to account for the ends of the actuator being capped. The hollow cylinder has an inner diameter of 12.7 mm (0.5 inches) and an overall thickness of 3.5 mm. The dimensions for the length of the cylinder and the inner and outer diameter of the cylinder is given by the following Figure 2.4. A detailed drawing is provided for more information by Appendix B.

*Figure 2.4: Length, diameter, and thickness of the actuator.*
Figure 2.4 shows the inner layer having a thickness of 1.7 mm and an outer layer thickness of 1.8 mm.

2.3 Mold Design

The soft actuator is created by using molds. There are two separate sets of molds. The sets of molds are referred to as the inner mold and the outer mold. Each mold set has a base and top part that are combined to create the cast of the soft actuator. The inner mold has the ridges protruding from the mold that creates indentions along the body of the soft actuator and is used to create the inner layer of the soft actuator. The indentions on the inner layer of the soft actuator will house the tilted helix fibers. It is important to know how the fibers are going to be wound around the inner layer. This will be explained in Chapter 5. The inner layer is formed from the inner mold with an inner layer thickness representing the thickness of the inner layer. Outer mold is slightly larger than the inner mold. It is present to cover and keep the fiber reinforcement in place. The outer layer is formed by the outer mold with a specific outer layer thickness in mind. Both outer and inner molds along with their base and top molds are given by Figure 2.5.
A key detail to note is how many fibers are being used. For the design of these soft actuators, there are two of the same fibers used that are evenly spaced from each other. This is due to the performance of the actuators when using one fiber. For the initial set of smaller soft actuators with one when pressurized, there are large bulges that occur between the spacings of the fiber reinforcements. These bulges are susceptible to leaks and bursting. Also, when the soft actuators are fabricated, there are not perfectly homogenous on all sides. Some bulges that occur are not similar in size. The bulges present uncertainty and error that may contribute to incorrect data. It would be difficult to represent the large bulges in theory. Including 2 fibers equally spaced hardly allows any bulges to form. This is the reason for the design choice for fiber reinforcements. An example of the bulges from the soft actuator is provided by the following Figure 2.6.
2.4 Fabrication Process

To create a fully functional soft actuator capable of coiling and uncoiling, a fabrication process is developed. Soft actuators will be composed of flexible hyperelastic material such as Dragon Skin 10 Slow [27]. The material of the fiber reinforcement will be Kevlar thread. Basic information about the materials used to create the soft actuators is referenced in Appendix C. Molds for the soft actuator are 3D printed. Depending on the
type of additive manufacturing process is chosen, the accuracy will change. There are two 3D printers that were used to create the molds for the soft actuator, Stereolithography (SLA) and Polyjet printer represented by Figure 2.7.

![3D Printers: SLA Formlabs Form 2 and Polyjet Objet 350 Connex.](image)

SLA printers use resin as print material. The print material used is clear resin. The polyjet 3D printer will be using nylon as the mold material. Depending on which 3D printer is used, there are different molds that will be printed and will result in different lengths and surface finish. The printed mold from the 3D printer is represented in Figure 2.8. The molds shown have a tilt angle of 51°.
Once the molds have fully been printed, the soft actuator is ready to be cast. The inner mold is used to cast the inner layer of the soft actuator. Dragon Skin 10 Slow has two different solutions that when mixed together will form silicon rubber. The solutions must have a mass ratio of 1:1 and be well-stirred to successfully create the silicon rubber. The mixed Dragon Skin 10 Slow solution will have air bubbles. These bubbles may cause small puncture holes whenever the soft actuator is pressurized meaning that air will seep out of the actuator. Numerous amounts of bubbles will lead to an uneven soft actuator. To eliminate the bubbles from the solution, it is best to use a vacuum pump and vacuum chamber to eliminate the bubbles from the solution. These steps create the Dragon Skin 10 Slow solution ready to be cast (Figure 2.9).
Once the Dragon Skin 10 Slow has the bubbles eliminated, the inner molds and a 0.5-inch metal rod are used. Dragon Skin 10 Slow is slowly poured into the base part of the inner mold. The 0.5-inch metal rod is gently placed in the inner set mold. The Dragon Skin 10 Slow solution fills the entire base part of the inner mold and the metal rod is submerged under the Dragon Skin 10 Slow solution (Figure 2.10).
Finally, the top and base parts of the inner mold are clamped together and the Dragon Skin 10 Slow must sit out for seven hours to cure. Once, the inner layer of the soft actuator is completely cured, I removed the soft actuator from the base and top parts of the inner mold set (Figure 2.11). An important detail to pay attention to is making sure the rod is in the center of the mold. If the actuator is leaning in any direction, then that side will have less material and will be more susceptible to tearing. A cap is used to keep the solution inside of the inner molds and the cap accurately adjusts the metal rod to be in the center of the inner mold.

Figure 2.11: Base and top parts clamped to cure Dragon Skin 10 Slow.

Wrap both sets of fibers around the soft actuator along the indentations from the protruding ridges from the molds tightly. When the actuator expands due to pressurization, there should not be any slack in the fibers. It is important to notice that if a large tilt angle
is used, the fibers may have difficulty staying in place along with the soft actuator due to the steepness of the tilted helix fiber reinforcement. The fibers tend to roll out of place. The soft actuator with the inner layer without the fiber reinforcement is given by Figure 2.12.

![Figure 2.12: Soft actuator's inner layer with indentions for the fiber reinforcement.](image)

The inner layer of the soft actuator with the tilted helix fiber reinforcement is represented by Figure 2.13.
Once, the fibers are tightly secured along the indentation of the soft actuator, I used the outer mold to cast the outer layer of the soft actuator just like what was done with the inner layer. I poured the Dragon Skin 10 Slow into the base part of the outer mold. For this time, the metal rod has the inner layer of the soft actuator attached to it. I placed this metal rod with the inner layer in the base part filled with Dragon Skin 10 Slow and allow each side of the inner layer to be covered with the Dragon Skin 10 Slow. I filled the base part of the outer mold with Dragon Skin 10 Slow and place the top part of the outer mold on top of the base part and clamp together. I let Dragon Skin 10 Slow cure for seven hours. This led to a hollow soft actuator. I removed the outer mold from the actuator along with the metal rod.
Now I capped the other end of the soft actuator. Recall the base part of the inner and outer mold. Whichever side of the actuator was located on the flat portion of the base part of the mold is the side that should be capped first. This is the side where the source of air pressure is applied. Figure 2.14 shows the flat portion of the base part of the inner and outer molds.

![Figure 2.14: Location of the first end needed to be capped on the actuator.](image)

To cap the end, I added the Dragon Skin 10 Slow solution to a small cup. I wrapped the end of interest of the soft actuator with Teflon tape and dip the end into the small cup. Teflon prevents the excess Dragon Skin 10 Slow from attaching to the outer surface of the soft actuator. The soft actuator is then vertically placed. I made sure the solution occupies 17 mm of the hollow soft actuator’s end. I used the Dragon Skin 10 Slow solution to cap the end of the hollow soft actuator. The solution is then cured for seven hours. I removed the actuator from the cup and remove the excess Dragon Skin 10 Slow and Teflon tape.
Then added a vented screw through the capped end of the soft actuator. I attempted to insert the vented screw through the open end to the capped end. Figure 2.15 shows the soft actuator with Teflon tape, being capped at the correct end, and the screw placed through the end that has been capped.

![Figure 2.15: End of soft actuator wrapped with Teflon tape. Actuator placed in the cup to cap the end. A vented screw inserted through the capped end.](image)

The capping process is performed for the other end of the soft actuator except with no vented screw. Once the other end cured for seven hours, I removed the soft actuator from the cup and remove excess Dragon Skin 10 Slow and Teflon tape. Finally, I attached the adapter for the air hose on the vented screw for the hose. The fiber reinforced soft actuator is prepared to be pressurized (Figure 2.16). Since the soft actuator is fabricated before the FEA model is developed, the mass of the actuator is measured and will be added to the FEA model in the FEA setup.
Some details must be mentioned about the fabrication of these soft actuators. The scale of the soft actuators will the difficulty of fabrication. There is very little room for error. The ridges protruding from the mold should not create large indentions in the surface relative to the thickness of the soft actuator or else the spacing between the fiber reinforcement and the inner surface of the actuator will be thin and the actuator will be more susceptible to leaks. Also, if the soft actuator has indentions for the fiber reinforcement that is too small, then adding the fiber reinforcement will be difficult fiber reinforcement with a high tilt angle. For example, through previous trials, fabricating a soft actuator with a large tilt angle $61^\circ$ and with a small thickness of 1.5 mm proved to be difficult. This is due to the indentation on the soft actuator not being deep enough to house
the fiber reinforcement. Since the larger the tilt angle becomes, the more tilted a helix will become, the fibers would fall out of the indentions. This is one of the details to pay attention to when constructing the soft actuators.
CHAPTER THREE
MATERIAL PROPERTIES

An FEA model must be developed so that the model can be compared to the experimental model. The first step is to derive the material model for the soft actuator. Dragon Skin 10 Slow is silicon rubber, therefore it is a hyperelastic material. From this information, a hyperelastic must be derived and used to create an FEA model of the soft actuator.

3.1 Hyperelastic Materials

Hyperelastic materials have a nonlinear stress-strain relationship; however, the material returns to its original state. Many hyperelastic models are considered for this experiment. For simplicity, there are three models of interest are chosen: Neo-Hookean, Mooney-Rivlin, and Ogden Models [16]. Neo-Hookean model is similar to Hooke’s law as the model can be used to determine the stress-strain behavior of a material that has large deformation. The same can also be said about the Mooney-Rivlin model, except for the number of invariants from the Cauchy-Green deformation matrix. Mooney-Rivlin uses two invariants while Neo-Hookean uses one invariant. This makes the Mooney-Rivlin model more accurate than the Neo-Hookean model. Ogden model differs from using invariants from the deformation matrix and uses principle stretch ratios. Also, Ogden models depend on the order, meaning the order of the strain energy density function changes. The order of the model determines the accuracy of the solution. Increasing the order of the model will
also increase the number of coefficients needed to represent that model. The order of the Ogden models used is 1\textsuperscript{st}, 2\textsuperscript{nd}, and 3\textsuperscript{rd} order.

The strain energy density function can be written in different ways depending on the hyperelastic model. Each model has certain material property values that affect the model. These values are found from gathering material testing data and curve fit the model to the data. With hyperelastic models established, a specimen is created. The specimen is used to gather material test data so that the coefficients of the hyperelastic models are identified.

### 3.2 Specimen Testing

A testing specimen is created to gather data. Due to limitations of how many testing machines available, the only test that will be performed will be the uniaxial test. Our specimen will be based on a dog specimen. A mold for the dog bone specimen is 3D printed. A cast is created out of the rubber material that uses the 3D printed molds which are represented by Figure 3.1. While the dimensions of the dog bone specimen are represented by Figure 3.2 with a thickness of 3 mm.

![Figure 3.1: Mold to create dog bone specimen out of Dragon Skin 10 Slow.](image)
While the specimen is placed on clamps of the uniaxial testing machine, there is a constant strain rate that is causing the specimen to elongate. At the same time, the force (Newtons) and the displacement (mm) is recorded to produce the force-displacement curve represented by Figure 3.3.
From the force-displacement curve, the nominal stress-strain plot can be derived from the information given. The original of the dog bone specimen is 30mm$^2$. This area is used to identify the nominal stress. While the gauge length of the dog bone specimen is 30 mm. The gauge length is used to identify the nominal strain. The nominal stress-strain plot is represented in Figure 3.4.
Figure 3.4: Nominal Stress-Strain plot due to uniaxial testing of Dragon Skin 10 Slow.

The previous figure is a plot of the nominal stress-strain data for the uniaxial test data for the material of Dragon Skin 10 Slow. The nominal stress slowly increases as the nominal strain constantly increases. At an estimated nominal strain value of 1.5, the stress drastically increases. This relationship is normal for hyperelastic materials.

3.3 Material Testing Results

Currently, the objective is to match the appropriate hyperelastic model with the test data for the FEA simulation. The hyperelastic models examined are the Neo-Hookean, Mooney-Rivlin, and Ogden models (1st-3rd). Before the comparison between all
hyperelastic models, it is important to identify which Ogden model will work best for the experiment. Through careful deliberation, Ogden 2\textsuperscript{nd} Order model is the best hyperelastic models compared to the 1\textsuperscript{st} and 3\textsuperscript{rd} models. Figure 3.5 qualitatively shows the hyperelastic models of Ogden 1\textsuperscript{st}-3\textsuperscript{rd} plotted against the uniaxial data.

![Nominal Stress-Strain Plot DragonSkin 10 (Ogden Models)](image)

*Figure 3.5: Ogden 1\textsuperscript{st}, 2\textsuperscript{nd}, 3\textsuperscript{rd} model comparison.*

Ogden 1\textsuperscript{st} order model’s curve does not match the uniaxial test data. Ogden 3\textsuperscript{rd} order model matches the uniaxial data as much as the Ogden 2\textsuperscript{nd} order model. However, Ogden 3\textsuperscript{rd} order model is a higher order system. The plots of Ogden 2\textsuperscript{nd} and 3\textsuperscript{rd} order models are similar. Since both models are relatively close in matching the material testing data, it is
best to use the lower order system. This means Ogden 2\textsuperscript{nd} order model is the best to use.

The coefficients for the Ogden models are given in Table 3.1.

<table>
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<th>ORDER</th>
<th>$\mu_1$ (MPA)</th>
<th>$\alpha_1$</th>
<th>$D_1$ (MPA)</th>
<th>$\mu_2$ (MPA)</th>
<th>$\alpha_2$</th>
<th>$D_2$ (MPA)</th>
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<th>$\alpha_3$</th>
<th>$D_3$ (MPA)</th>
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<tr>
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<td>0</td>
<td>6.75E-02</td>
<td>1.45</td>
<td>0</td>
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</tr>
<tr>
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<td>0</td>
<td>1.68E-02</td>
<td>5.50</td>
<td>0</td>
<td>-2.81E-02</td>
<td>-11.12</td>
<td>0</td>
</tr>
</tbody>
</table>

*Table 3.1: Coefficient for Ogden Models. $\mu$ represents the shear modulus (MPA) and $D$ represents material constant that includes the bulk of modulus (MPA).*

Ogden 2\textsuperscript{nd} order, Neo-Hookean, and Mooney-Rivlin curves are compared qualitatively to see which model the best for the simulation is. The approximate curves are given by the following Figure 3.6. The coefficients for the Neo-Hookean and Mooney-Rivlin models are given in Table 3.2.
Table 3.2: Coefficients for Neo-Hookean and Mooney-Rivlin. $C_{10}$ represents half of the first shear modulus and $C_{01}$ represents half of the second shear modulus. $D_1$ represents a material constant that includes the bulk of modulus.

According to the previous figure, the most appropriate hyperelastic model is the Ogden 2nd order model. Neo-Hookean and Mooney-Rivlin models show a strong correlation with the experiment. However, Ogden 2nd order is closer to resembling the material test data than the other models. For the FEA simulation, the material model used for the soft actuator is Ogden 2nd order model.
CHAPTER FOUR
SIMULATION/EXPERIMENTAL SETUP

Validation of the research objective will consist of experimentally gathering of data to show coiling and a theoretical simulation to qualitatively and quantitively compare the results to the experimental data. The type of model used will be a Finite Element Analysis (FEA) model. The FEA setup portion is assisted due to the softroboticstoolkit [21].

4.1 FEA Setup

Before the FEA setup, there are assumptions that must be made about the material. Dragon Skin 10 Slow is assumed to be isotropic, having the same material properties in the same direction. Also, the material is assumed to be homogeneous. This has the backing of the elimination of air bubbles and centering the metal rod in the mold as stated previously. Finally, the material is incompressible. Also, the material for the fiber is Kevlar Thread and the only thing needed is the Young’s Modulus 31067 MPA [21]. These are pieces of information to fully identify the material properties.

For the FEA model, the physical model is transferred to the FEA software. The FEA simulation will be performed by using *ABAQUS*\textsuperscript{TM} software. The material information stated previously is placed in for the FEA model. For the simulation, the soft actuator will be vertically hung and completely fixed at one end (Figure 4.1), meaning hanging upside down. Fixed meaning that there will be no translation and rotational displacement. The reason for this is due to the additional complexities of having the soft actuator in any different orientation. The fixed boundary conditions represent the side where the soft
actuator will be hung from where the source of air is applied. For example, if the soft actuator is horizontally placed, additional moments and uneven force distribution will be applied even when the actuator is at rest.

![Figure 4.1: Fixed boundary condition.](image)

For experimental purposes, the soft actuator will be pressurized internally. The complete inner surface of the soft actuator is being pressurized. For both the experiment and the simulation, the pressure will begin from 0 MPA to 0.103421 MPA (12 psi) for 4 seconds. Also, there will be a gravitational force. The mass recorded from the soft actuator previously is added to the FEA model. ABAQUS™ only uses the density for mass considerations, so the volume and mass of the actuator can be used to find the density.

The FEA model must have a mesh associated with it. The mesh shape assigned will be a tetrahedral shape. The mesh shapes of interest that are provided by ABAQUS™ are tetrahedral and hexahedral shapes. Between the shapes, tetrahedral shapes are more commonly used compared to hexahedral shapes. Also, tetrahedral shapes are more commonly used for complex geometries. With the introduction of the model being completely capped at both ends, along with the curved geometry, mesh generation was difficult using hexahedral shapes. Also, the tetrahedral shapes are quadratic rather than the
linear. There are more degrees of freedom associated with the quadratic tetrahedral shapes. The accuracy of the solution will be greater with quadratic tetrahedral elements compared to the linear tetrahedral elements. Since the material used is hyperelastic and incompressible, an issue of volumetric locking occurs. Incompressible hyperelastic materials can cause the volumetric locking of elements. This will mean that the elements are too stiff. There are numerous ways to solve this issue, but of interest is using hybrid elements. Hybrid elements introduce degrees of freedom which will allow the overly stiff terms to be removed from the equations used to solve the FEA simulation. Again, the elements used are quadratic tetrahedral hybrid elements. The inner and outer layers are merged together then the meshes of the layers are merged. For how ABAQUS™ refers to these elements, it is given by Figure 4.2.

![Figure 4.2 ABAQUS™ interface for the element type. Notice the options that are chosen. The element type given for this specific mesh is a C3D10H (A 10-node quadratic tetrahedron, hybrid, constant pressure)]
The main body of the actuator is composed of the inner and outer layer of the soft actuator and the layers are merged together. Using the element type C3D10H, referred to by ABAQUS, the mesh generation for the main body of the soft actuator is represented by Figure 4.3.

![Figure 4.3: Mesh generation for the soft actuator and fiber reinforcement. Mesh size of 3mm.](image)

The fiber reinforcement is a different part from the main body of the soft actuator, thus the mesh will be different. The fiber reinforcement has a small mass and is thin, to the point of where it is considered to not have a volume, so actual shapes such as hexahedral and tetrahedral shapes are not applicable for this fiber reinforcement. Fiber reinforcement will be treated as a quadratic beam. The ABAQUS™ element detail is B32. Then the mesh is generated for the fiber reinforcement. Figure 4.3 also shows the mesh of the fiber reinforcement.

Once the fiber reinforcement and the main body for the soft actuator have meshed, the fiber reinforcement can be tied to the inner layer of the soft actuator using a tie constraint. The tie constraint ties the node region of the fibers and the surface of the actuator body together. The FEA model is ready to be simulated.
4.2 Experimental Setup

For the experiment, it is important to extract relevant data to compare to the FEA simulation. The type of data extracted will be concerning the location of nodes. When it comes to the soft actuator, there will be markings on both sides of the actuator and these markings will serve as nodes. For each node on one side, there will be another node on the opposite side of the actuator. The length between one node and its opposite node should be the diameter of the actuator at rest. These will be the outer nodes. Figure 4.4 shows twelve equidistant node markings on one side of the actuator. Each node is approximately an inch apart. Also, Figure 4.4 shows nodes chosen for the FEA model. The reasoning for this is to identify the center node between the opposing nodes. Figure 4.4 shows the center node as a red dot and the nodes opposite from one another are black dots. The nodes highlighted in yellow and green represents Side 1 and Side 2 of actuator respectively. The gray lines connect the two corresponding nodes that relate to one another. Center nodes represent the motion of the tube axis. From there, there is a certain number of center nodes along the body of the soft actuator. A larger quantity of nodes is chosen for the FEA model, but twelve nodes from the FEA model that matches the experimental model in its original position are chosen to quantitatively compare both experimental and FEA models during pressurization. The 3D positioning of nodes on the outer surface of the actuators is tracked by a function of pressure in both models. Then for each model, the center nodes are found and connected to show the overall motion of the actuator.
Figure 4.4: Schematic of node markings and actual markings. The left schematic is before and after pressurization. Yellow and green highlighted nodes are Sides 1 and 2 of actuator respectively. Gray lines connect the corresponding nodes for both sides. The right figure represents the experimental model having 12 node markings on one side and the selected nodes for the FEA model.

Two Intel Realsense Depth Camera D415 cameras are used to record the 3D positioning of the outer nodes on each side (Figure 4.5).

Figure 4.5: Intel Realsense Depth Camera D415

These cameras are directly opposite from each other and labeled Camera 1 (C1) and Camera 2 (C2). Camera 2 coordinates will be transferred to the coordinates of Camera
1. This is because Camera 1 and the ABAQUS™ is observing the actuator the same way. Camera 2 is observing the back of the actuator. However, to this, the cameras are calibrated, so that the cameras are the same in magnitude, but opposite directions. The X-axis and Y-axis should be different in direction between the two cameras. The soft actuator is vertically hung from a cube structure constructed from aluminum extrusions. The cameras are calibrated by creating a reference point between both cameras. For more detail on the specs and use the camera appropriately, refer to Appendix D. The reference point used is located at the red dot for Figure 4.6. A thin sheet of paper with equidistant dots on both sides are used as the reference points. Each camera should read a point to be the same distance in magnitude, but different in direction. Once all the points are equal in magnitude distance, but different in X-axis and Y-axis directions, then the cameras are calibrated.

The red dot in Figure 4.6, is a brake that slides along the aluminum extrusion located at the center of the cube structure. During calibration, the thin piece of paper is hung from the brake. During the experiment, the soft actuator has a circular clamp attached to the top end and attached to the brake. A schematic of the experimental setup and an actual figure of the experimental setup is represented in Figure 4.6.

![Figure 4.6: Schematic and real experimental setup.](image-url)
Now the information about how the pressure is applied to the actuator needs to be established. A valve is used to supply pressure. The valve is open enough to allow 48 psi. The air pressure travels through a hose. The hose goes into a transducer (CONTROLAIR Type 900-ELA Zero Based Transducer, 0-10 VDC Input Signal, 0-15 (0-1) Output Range PSI (BAR), 25-65 (1.72-4.5) Supply Pressure PSI (BAR)), to regulate the air flow and another hose exits the transducer where the air has been regulated. The hose exiting the transducer is attached to the end of the actuator. The transducer is attached to a DC power supply (TENMA 72-2690 Digital-Control DC Power Supply 30V 5A) supply and a function generator (Tektronix 3022C, 250 MS/s, 25 MHz, Dual Channel, Arbitrary Function Generator). DC power supply supplies the power to regulate air pressure. The DC power has the voltage and amps set to 9.8 volts with 0.002A respectively. The function generator relates the voltage to the air pressure in a certain fashion. For example, the function generator will relate the supplied to the air pressure by using DC waveforms. This will allow the voltage to be linearly related to the air pressure. Through calibration of the transducer, to produce 1 psi of pressure, the voltage supplied is roughly 0.330 volts. All the setup for how pressure will be applied to the soft actuator is given by Figure 4.7 This is how the pressure will be supplied to the soft actuator.
With both the FEA and experimental setup completed, along with both experimental and FEA models, the models are tested with their respected setup. The FEA model can be ran through a simulation and the experimental model can be pressurized. Results from both models will be compared.
CHAPTER FIVE

RESULTS

The following are the FEA and actual experimental data recorded from testing. A comparison is made with a tilt angle of 51° to identify if it is possible to construct an experimental model that can match the FEA model.

5.1 FEA Results: Mesh Convergence Study

The accuracy of the FEA model is verified by using the mesh convergence study. The mesh convergence study is used to verify if the model can converge to a solution. This decreases the time needed to simulate the model, due to a smaller mesh size. The type of mesh used is quadratic tetrahedral elements (C3D10H) and quadratic beams (B32). During the mesh convergence study, the mesh sizes changes which will result in the number of elements changes. During the changes of elements, what the results should show is a consistency between the mesh sizes that has the same values for some parameter being measured. The parameter chosen will be the total displacement (mm) of the soft actuator. The mesh convergence study features a mesh size range between 2 mm and 10 mm. The results of the mesh convergence study are represented in Table 5.1 and Figure 5.1.
Table 5.1: Mesh convergence study numerical results. Notice that for mesh sizes of 8, 9, and 10 mm have the same total displacement. It is important to note that the simulation with the mesh size of 6 failed after numerous attempts. Excluding the failed simulation, the average and standard deviation values are more tolerable.

![Figure 5.1: Mesh convergence study plot. The red dot is the mesh size 6 and it failed to complete the simulation.](image-url)
As shown by Figure 5.1, the mesh convergence study shows average constant total displacement of 227.9 mm with a standard deviation of 36.9 mm. This data includes the failure of an FEA simulation at a mesh size of 6 mm, the red dot in Figure 5.1. When excluding this data point, the average is total displacement is 240.7 mm with a standard deviation of 7.8 mm. There is a small variation between different mesh sizes. The current model is a good model to use. The time to complete the simulation takes around 2 hours, except when the mesh size is 2 mm. The mesh size of 2 mm drastically takes longer than the other meshes. The accuracy of the mesh will be weighted more than the time of the simulation. The mesh size chosen for the simulation is 3 mm for the FEA model.

Since the mesh convergence study is a success, the model of the soft actuator can be simulated. A reminder of the basic FEA setup is that the soft actuator will be fixed at completely one end and vertically hung. Also, the loading conditions of the model will feature an internal pressure of 0 to 12 psi for 4 seconds. The actuator is tested and then the nodal positions of the nodes relative to the cameras will be recorded.

5.2 Comparison between Standard and Tilted Helix

The primary focus is to show how different does a tilted helix fiber reinforcement differ from the standard helix fiber reinforcement of a soft actuator. As stated previously, there is hardly any difference between the tilted and standard helix except for the Z-axis equation of the helix (equations (3) and (4)). For this comparison, only an observation from the FEA models of a soft actuator with a tilted and standard helix fiber reinforcement will be used. The FEA models used are smaller scale in size to reduce computation time. The
following Figure 5.2 displays how a tilted and standard helix fiber reinforcement will affect the soft actuator.

Figure 5.2: FEA simulations actuator of standard and tilted helix fiber reinforcement. (a) Standard helix fiber reinforcement actuator at rest. (b) Tilted helix fiber reinforcement actuator pressurized. (c) Tilted helix fiber reinforcement actuator at rest. (d) Titled helix fiber reinforcement actuator pressurized.

Figure 5.2a and Figure 5.2b represents the FEA model with a standard helix fiber reinforcement before and after pressurization. When the standard helix model is pressurized, the model elongates and twists. However, for the tilted helix model, Figure
5.2c and Figure 32d, the model elongates by a little, twists, and bends. The motion of bending and twisting together will result in coiling motion. The model, however, cannot bend and twist effectively due to how small the model is (Appendix A). This comparison does show a notable difference between both the standard and tilted helix, so an assumption is made that a tilted helix fiber reinforcement will affect a soft actuator differently from a standard helix fiber reinforcement. From this result, a more in-depth look can be gathered from a tilted helix soft actuator.

5.3 FEA: Tilted Helix Results

The tilt angle of these results is 51°. It is important to note how the fibers are orientated. From the top of the FEA model, the fibers are wrapped in a counterclockwise fashion (Figure 5.3). The motion of the coiling is predicated on how the fibers are wrapped around the actuator. Counterclockwise and clockwise windings from the top view of the actuator, will cause the FEA model to coil in the clockwise and counterclockwise directions respectively from the top.
Figures 35a-d shows the FEA model pressurized from 1-4 seconds. Each second correspond to 3 psi. At the beginning of the simulation, the actuator slowly bends towards the left. This is particularly due to how the fibers were wound for the first two seconds. At one second, the pressure is 3 psi, and the model barely shows any motion, except for a little bending. At two seconds, 6 psi, the influence of bending is increased. However, after the first 2 seconds, the model twists and bends more noticeably. This motion continues until the end of the simulation. From observing the model at the end of the simulation, the actuator noticeably coils and elongates. Figure 5.4 shows the actuator at a pressure at its resting position at 0 psi.
The original position of the FEA model of the soft actuator is indicated in Figure 5.4. All future FEA models will have the same resting position as the soft actuator with the tilted helix fiber reinforcement of 51°. Figure 5.5 has the FEA model as it changes with respect to pressure/time. For every second, there will be 3 psi being applied. This will continue to take place until 4 seconds or 12 psi.
The model with the tilt angle of $51^\circ$ shows relevant coiling. As seen by the previous figure, the soft actuator begins to bend towards the left and twist into the background. With these results, the model for the soft actuator can be qualitatively compared to the experimental data.
5.4 Experimental Results

Using the fabricated soft actuator and the tilt angle of 51°, the experiment previously discussed can be used and data can be gathered from the experimental model. The soft actuator is supplied with a pressure from 0 psi to 12 psi. The reason for this is due to the soft actuator having leaks and tears when the pressure is increased to a pressure level above 12 psi. Figures 36 is the experimental model at rest and 0 psi and this will be the resting position for the soft actuators in the future sections.

![Experimental model of the soft actuator at the rest position.](image)

Figure 5.6: Experimental model of the soft actuator at the rest position.

Figure 5.7 shows the experimental model pressurized from 3 to 12 psi in 3 psi increments. Qualitative conclusions are made by comparing Figures 35 and 37 to each other.
Figure 5.7: Pressurized experimental model with a tilt angle of 51°.

Qualitatively speaking the actuator bends in towards the left side and begins to twist into the background. For the smaller amounts of pressure (1~6 psi), the soft actuator coils by a small amount, but when the pressure supplied rises above that range, the soft actuator coils more effectively. Also, the cameras during the experiment recorded the data from
both sides to quantitively receive the data. Since both quantitively and qualitatively have been recorded, the experimental and FEA model of the soft actuator can be compared simultaneously.

5.5 FEA Simulation and Experimental Comparison

Now that the quantitative and qualitative data has been found, the FEA and experimental results can both be compared to one another. Qualitative speaking, the experimental and FEA models are not matching exactly. It appears that more pressure is needed for the experimental model to get the same motion as the FEA model. For comparison purposes, the experimental model was pressurized to 12 psi and the pressure was changed in the FEA model to find out which pressure was needed to get the same motion as the experimental model. At estimated 2.84 seconds, meaning at 8.51 psi, the FEA model is similar to the experimental. A side by side comparison can be seen in Figure 5.8.
The FEA and experimental models are similar in shape and motion. Both models bend towards the left and twists in a clockwise fashion relative from the top. Since it is bending and twisting, this is referred to as coiling. Also, for low pressure (0-6 psi), the soft actuator does not coil as effective as when the pressure is at high (6-12 psi). The reason for the soft actuator’s behavior is due to high pressure being applied to Dragon Skin 10 Slow causing more stretching than at a lower pressure.

From Figure 5.8, finding the center node at each point of the soft actuator is used for both the FEA model and the experimental model and the quantitative data is shown in Figure 5.9. The FEA model can take numerous nodes on both sides of the model and the center node can be calculated. However, for the experimental model, there has to be a set value of nodes to gather data from due to the difficulty with recording an excessive number.
of nodes. The number of nodes on each side of the experimental model is set to be 12
nodes.

A coordinate system is established. The top and center of the FEA model are given
as the origin position (0,0,0). It is important to remember what the positive and negative
directions are of both the experimental and FEA model. Information about the coordinate
system for the cameras and ABAQUS™ is in Appendix D. It is important to remember to
transition all experimental data from both cameras to ABAQUS™ coordinates. This will
make both FEA and experimental data have the same coordinate system. However, after
the experimental and FEA models are both in the same direction, they need to be transferred
to the Right-Hand coordinate system (Positive X-axis is right, Positive Z-axis is up,
Positive Y-axis is backward). The results of Figure 5.9 are in the same plane as both the
experimental and FEA models. The results from the experimental model and results from
the FEA model are compared and shown in Figure 5.9. The reason for the current
orientation of how the data is presented is because of the difficulty in getting a visual from
the XY plane and the redundancy of using the YZ plane.
Figure 5.9: Quantitative comparison between experimental and FEA models with a tilt angle of 51°.

Notice that both the FEA and experimental data have almost the same motion at their respective pressure, but the positioning of the nodes are different. Qualitatively speaking, the FEA and experimental data are similar. Assumptions are made for why the experimental results are not in complete agreement with the FEA results.

There are some reasons for why the quantitative data does not match for both models. The fabrication process of making the experimental model consisted of many steps. The hyperelastic models could have used more material testing data. The soft actuator could have still some small bubbles that may cause the actuator behavior to be
inaccurate. These are just a few errors that are briefly introduced and will be elaborated more on in the conclusion section.

The quantitative data and qualitative data for the FEA and experimental models did not directly match. Both models share the same motion. Some errors may have caused the inaccuracies between the FEA and experimental models. Having the data and results of the soft actuator with a tilt angle of 51° is important to have as there is some validation in having a helix with a tilt angle. The tilt angle of fiber reinforcement causes coiling. To better understand the impact of the tilt angle on the coiling effectiveness, smaller and larger tilt angles are used in the next section.
CHAPTER SIX
PARAMETRIC STUDIES

A parametric study is performed to show how changing the tilt angle will result in a change in the coiling effectiveness. An assumption is made about what is expected to be seen. Notice how when applying a standard helix fiber reinforcement will result in twisting and no bending, but a tilted helix fiber reinforcement produces twisting and bending. An assumption is made when changing the tilt angle, the influence bending will increase or decrease. Thus, coiling and uncoiling effectiveness will increase or decrease. The first tilt angle 51° used was used as the control for this parametric study. An additional two tilt angles will be used for the study. A smaller tilt angle compared to the control tilt angle is selected to prove less coiling will take place. The other tilt angle will be larger than the control tilt angle to show a better coiling diameter.

6.1 Results from smaller and larger tilt angles

Both FEA and experimental models are constructed the same way as the actuator with a tilt angle of 51°. With the exception of the tilt angle of the helix reinforcement.

6.1.1 Larger tilt angle: 61°

Figure 6.1 and Figure 6.2 are the FEA and experimental models respectively when pressurized for the tilt angle of 61° degrees. The rest position used for FEA and experimental models is shown in Figure 5.4 and Figure 5.6.
Figure 6.1: Pressurized FEA model with a tilt angle of 61°. (a) 3 psi. (b) 6 psi. (c) 9 psi. (d) 12 psi.
Qualitatively speaking, both FEA and experimental models are similar in motion. However, it takes a different amount of pressure to achieve the same motion for both models. With this current tilt angle, the FEA model appears to be coiling more outward. The quantitative data will help understand the influence of a large tilt angle. An
approximation is made to see how different the pressure is for each model, the same method performed for a tilt angle of 51° is performed for the 61°. The experimental model at 12 psi is compared to the FEA model that has almost the same motion and shape. This is found by using the nodal data gathered from the experiment. Figure 6.3 shows the nodal data when the FEA and experimental data are visually similar.

Notice that both FEA and experimental results are similar. The tilt angle, however, both results are different depending on the pressure as the experimental model has the same shape at 12 psi as the FEA model at 9.603 psi. Notice how different these results were from the results from when the tilt angle was 51°. When the model has a tilt angle of 61°, the
model seems to bend outward more compared to when the tilt angle is 51°. Theoretically, this is valid. When the tilt angle increase, the more outward the actuator will bend. Remember the twisting and bending motions are what produces the coiling. Specifically speaking, a high tilt angle (relatively speaking 61° is large compared to 51°) will cause the bending motion more than the twisting motion. Thus, the reason why the model seems to bend outward.

6.1.2 Smaller tilt angle: 41°

Using this knowledge, a smaller tilt angle will result in less influence of bending, leading to more coils being developed. In other words, twisting will be more noticeable than bending with a smaller tilt angle. The following results are when the soft actuator has a tilt angle of 41°. The FEA and experimental results are given by Figure 6.4 and Figure 6.5 respectively.
Figure 6.4 Pressurized FEA model with a tilt angle of 41°. (a) 3 psi. (b) 6 psi. (c) 9 psi. (d) 12 psi
Notice that for a tilt angle of 41°, the models have the same motion as the previous actuators with different tilt angles. However, these observations show the actuator coiling more with a lower tilt angle. This is to be expected due to some of the bending effectiveness being taken away as the tilt angle decrease. The actuator does not bend as much as the previous actuators, but it coils more than the others. Now, quantitative data is needed to
further the understanding of a lower tilt angle. The quantitative data is shown in Figure 6.6. Lower pressure is used due to how susceptible the actuators with a low tilt angle can result in tears and leaks.

![Experimental vs. FEA (Tilt Angle 41°)](image)

*Figure 6.6: Quantitative comparison between experimental and FEA models with a tilt angle of 41°.*

Quantitatively, the FEA and experimental data are not the same. The experimental data appear to show more coiling which coincides with what is assumed about a smaller tilt angle, but the FEA data does not show such relation. With a smaller tilt angle of 41°, the influence of bending is lessened. Relative to the tilt angles of 51° and 61°, the bending produced is significantly less. A soft actuator with a tilt angle of 41° results in more coiling.
due to how little the actuator bends, but relative to the other tilt angles, twisting is more influential, which agrees of what was stated previously. For more results from the soft actuators, refer to Appendix E.

Overall, the changing of the tilt angle shows that the lower the angle is, the more possible coils that may occur for a soft actuator. For a large tilt angle, the actuator tends to bend outward and not coil as much. The tilt angle will affect the bending of an actuator. Since bending and twisting together will contribute to coiling. Then the tilt angle affects coiling performance.

### 6.2 Predicted shapes while changing tilt angles and pressure

Experimentally, it is difficult to gather data from numerous nodes, but using the FEA model, it is possible. Gathering data from the FEA models using numerous nodes, for example, 100 nodes, with tilt angles of 41°, 51°, and 61°, the full shape of the actuator can be more accurate than just choosing 12 nodes. Also, while changing the tilt angle, it will be beneficial to change the pressure too. The change in pressure will be from 0-12 psi by increments of 3 psi. Using this information, a plot of different actuator shapes can be constructed in the form of Figure 6.7.
This figure is just to show the predicted shapes of all the possibilities that could happen when changing pressure and tilt angle. As the tilt angle increases, the number of coils and elongation increases. Decreasing the tilt angle results in more outward bending. Also, pressure has a greater visual impact on smaller tilt angles. For high pressure and low tilt angle, the actuator has more coils. The previous figure makes it easy to visualize the impact of pressure and tilt angle. Figure 6.8 shows the overhead view of the soft actuator at different pressures and tilt angle. Also, Figure 6.8 shows the actuators with different tilt angles at a pressure of 12 psi. This verifies the claim that a lower tilt angle (41°) has more coils and the higher tilt angle (61°) bend more outward.
Figure 6.8: Predicted overhead views of actuators with different pressure and tilt angles.
7.1 Conclusion

A fiber reinforced soft actuator with a tilted helix fiber will result in coiling and uncoiling motion when pressurized. By purely observing both the FEA and experimental models, and the models are similar in their motion. However, there may be some sources of error that prevent a completely valid quantitative result.

The chosen hyperelastic model was the Ogden 2nd order model. Observing how the FEA model can similarly match the experimental model for a certain pressure proves that there are some aspects of the material model not be fully realized. For example, Ogden 2nd order model outputs parameters, but these parameters may be incorrect due to the material testing. Only one set of data was taken, uniaxial test data, to generate the material model. More material testing is needed to produce the realistic material of Dragon Skin 10 Slow. There are multiple ways to get make the Ogden 2nd order model accurate. Choosing the material parameters or running additional material tests. ABAQUS™ only allows test data from Uniaxial, Biaxial, Planar, and Volumetric tests. With the additional tests, the material model will become more realistic to Dragon Skin 10 Slow. An issue that arises is considering other tests that cannot be inputted in ABAQUS™. For example, observing the motion of the soft actuator will indicate that there will be a shear stress acting actuator. ABAQUS™ cannot take shear test data. This is where the parameters of the Ogden 2nd
order model is needed. Calculation of the parameters can be performed analytically from all the tests.

Another source of error includes the number of steps of the fabrication process. With so many steps to consider, there could have been small missteps while constructing these soft actuators. For example, not having all the bulges out of the soft actuator can provide inaccuracies. Also, the amount of material on all sides of the actuator may not have been even. Some of the fibers could possibly be too loose or became undone from its indentations. The fabrication portion takes a few days, which leaves the possibility of some error occurring.

Fiber reinforced soft actuators can have unique motion primarily depending on the structure of the fiber reinforcement. A Soft actuator with a normal helix fiber reinforcement twist and elongate when pressurized. Bending does not occur. Bending occurs when the fiber reinforcement has a tilted helix structure. This is due to the influence of the tilt angle. Just including a tilt angle will allow some bending, depending on how large the tilt angle is. Thus, bending and twisting results in coiling. There is not a clear identification of how to numerically calculate which motion, bending or twisting, has a greater effect on the coiling motion. Qualitatively speaking, the influence of bending can be determined by examining the changing of the tilt angle.

A parametric study was conducted to show the influence of the tilt angle. Since there is noticeable twisting through FEA model simulation, changing the tilt angle will apply to the bending effectiveness and will affect coiling. For a smaller tilt angle, the bending motion is not that evident, but the twisting motion is dominant. This will result in
more coils, but less coiling diameter. A larger tilt angle will show more of a bending motion than the twisting motion. There will be fewer coils, but the coiling diameter will be larger. This proves soft actuators are capable of coiling and uncoiling motion. Thus, validates the statement about a tilted helix fiber reinforcement will cause coiling compared to standard helix fiber reinforcement.

Soft robotics paves the way for a new age of robotics. The compliance of soft robots creates more degrees of freedom for movement, which makes the design process simple compared to the design process of rigid robots. Through the focus of this research, the design of the soft actuator is rather simple. The only drawback of soft robots is the difficulty in understanding how the robots will behave when actuated. However, when fully understanding what creates certain movement for soft robots, then soft robots can be used in more effective situations.

7.2 Future Work

As previously stated, there are some aspects of this research that may lead to some inaccuracies in the results gathered. These inaccuracies can be improved on for future work.

First and foremost, the design of the soft actuator should be at a larger scale. For the soft actuators used for this research, a change of even 1 mm in the thickness, relatively low resolution, will affect the overall performance of the actuator. Also, a larger model will open many possibilities for different fabrication processes. One of the reasons 3D printing was used was because of the high resolution can be achieved. Scaling up the current models
for this research will result in a higher resolution that can affect the performance of the soft actuator, which can allow us to use different machines with low resolution to fabricate the molds.

More material test data will be gathered in terms of biaxial, planar, volumetric, and shear test. Using these tests, ABAQUS™ can output the parameters for a certain material model or if a specific material model is chosen, the parameters for that model can be found numerically.

A key factor that was being introduced was about bending. The tilt angle plays some role in bending. However, there is not an emphasis on the twisting motion, since both bending and twisting play roles in coiling. An assumption is that the pitch of the helix may contribute to the twisting. Different actuator with different pitches is anticipated to be created to see what effect, if any, the pitch has on the twisting behavior.

Some additional considerations include understanding the forces caused by the soft actuator. For the Erodium Cicutarium to burrow its way into the ground, there must be an applied torque and axial force. Now that the actuator is showing coiling, the next step would be to identify the force and torque being applied and attempt to control the force and torque so that it can further the use of soft actuators that can be used in potential applications.

Also, different analytical models besides the FEA models must be evaluated. For example, using an analytical model in some soft actuators with a standard helix fiber reinforcement produced more accurate results compared to the FEA model [17]. Exploring
a more accurate and simpler model for a soft actuator with a tilted helix fiber reinforcement could lead to a better comparison with the qualitative and quantitative experimental data.

Finally, more soft actuators with smaller and larger tilt angles will be designed and fabricated. More testing samples, in terms of the soft actuators, will allow for more data to be analyzed. The more test samples that can be used, the easier it is to see a trend between changing the tilt angles and how much coiling can occur. With these ideas for future work, these plant-inspired soft actuators will pave the way for a new innovative family of soft actuators.
APPENDICES
Appendix A

Previous Smaller Actuators

The first iterations of actuators were shorter in length, relative to the current iteration, as the length of the soft actuators were an estimated 6 inches. For the shorter actuators, the total elongation is not as larger as the current iteration of actuators. With these actuators, the thickness had to be smaller. There is no thickness to length ratio value, but if the length of the actuator is small, then this means that the thickness must be smaller to be considered thin. With the smaller thickness for the smaller actuators, the amount of pressure these actuators can withstand is smaller than the current iteration of actuators. Since the actuator thickness has to be smaller, the actuator will be difficult to fabricate due to the 3D printed molds has to be printed more accurately to have exact thickness. Therefore, the smaller actuators cannot take 12 psi like the previous actuators. Also, there is a limit to how much these actuators can have bending and twisting motion as represented by Figure A-1. As shown by Figure A-1, the actuator pressure is estimated to be about 6 psi. There is a limit to how much these actuators can elongate, and this is the reason for the larger actuators. To produce more coiling, withstand more pressure, and the mold design.
Figure A-1: Small pressurized soft actuator.
Appendix B

Drawing File of Soft Actuator

Figure B-1: Drawing file for the soft actuator.
### Appendix C

## Bill of Materials

**Figure C-1: Bill of Materials: All materials needed for the soft actuator**

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>SUPPLIER</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vented 18-8 Stainless Steel screws, 10-32 thread</td>
<td>McMaster</td>
<td>1</td>
</tr>
<tr>
<td>Aluminum Female Threaded <strong>10-32</strong> Hex Standoffs</td>
<td>McMaster</td>
<td>1</td>
</tr>
<tr>
<td>Nylon adapters, 1/8&quot; ID tube to 10-32 male threaded pipe</td>
<td>McMaster</td>
<td>1 Pack (10 total)</td>
</tr>
<tr>
<td>Nylon adapters, 1/8&quot; ID tube to 10-32 female threaded pipe</td>
<td>McMaster</td>
<td>1</td>
</tr>
<tr>
<td>Antistatic polyurethane tubing, 1/8&quot; ID, 1/4&quot; OD, 1/16&quot; Wall Thickness</td>
<td>McMaster</td>
<td>1 (10ft)</td>
</tr>
<tr>
<td>Kevlar thread</td>
<td>McMaster</td>
<td>1 (300yd spool)</td>
</tr>
<tr>
<td>1/2&quot; diameter, 304 Stainless Steel Rods with Certification (*Selection Process: Round, Solid, 304 Stainless Steel, 1/2&quot; diameter, Length: 2ft)</td>
<td>McMaster</td>
<td>1 (2ft)</td>
</tr>
<tr>
<td>Teflon Pipe Tape, 1/2&quot; wide</td>
<td>McMaster</td>
<td>1</td>
</tr>
<tr>
<td>Dragon Skin® 10 Slow</td>
<td>Smooth-On</td>
<td>Trial Unit Net Wt: 2lbs</td>
</tr>
</tbody>
</table>
Appendix D

Cameras and Coding

The Intel Realsense Depth Camera D415 are vital devices that assisted in gathering the experimental data. Some technical specifications must be considered when using these cameras. The minimum distance an object of interest can be so readings can be gathered is 0.3m from the front of the camera (depth, Y-axis). The range of the camera is around 10 m. The depth field of vision is $65^\circ \pm 2^\circ \times 40^\circ \pm 1^\circ \times 72^\circ \pm 2^\circ$ (Horizontal x Vertical x Diagonal). This set of information can be found using the manual from the camera.

Outside of the technical specs being used, there are important details to consider when using these cameras. The cameras were on a magnetic stand to elevate them off the ground. The cameras needed to be mounted. One 1/4-20 UNC thread mounting point was located on the camera to allow the camera to elevate. Also, the camera will read dark objects, so a dark background is used to gather quantitative data, then the camera may pick up the background and not the markings of the actuator. There must be a large contrast between both markings on the actuator and the surrounding areas.

The Intel Realsense Depth Camera D415 is used to gather the 3D positioning of the outer nodes of the actuator. The cameras must be operated through coding software and language. With the use of Sublime Text 3 and the programming language of Python, the code to record the 3D positing of nodes is found. Figure D-1 shows the code for the cameras.
import necessary packages

deposit pyrealtime as rc
deposit numpy as np
deposit cv2
from matplotlib import pyplot as plt
import math
import sys
import platform
deposit cv

---

# declare variables

# picture properties
rows = 720
columns = 1280
f_rate = 15

# color
blue = (255, 0, 0)
green = (0, 255, 0)
red = (255, 0, 0)
yellow = (255, 255, 0)

# set program flags
step_1 = False
step_2 = False
step_3 = False
step_4 = False

---

klick_counter = 0
x = 0
y = 0
ch_pr = mp.canvas((13, 13))
# coordinates
color_picture = np.zeros((2))

---

# ---

def get_mouse_position(event, x, y, flags, param):

gfx = event.x, event.y
klick_counter += 1

if event == cv2.EVENT_FLAG_BUTTDOWN:
    print('button clicked')

---

def good_features_to_track(gray_color):
    corners = cv2.goodFeaturesToTrack(gray_color, 1, 0.01, 10)
corners = np.int32(corners)
for i in corners:
    x, y = i.ravel()
    return x, y

---

# adjust properties

print('Python Version: %s', sys.version)
print('Windows Version: %s', platform.platform())
```c
// Stream Properties

pipeline = pipe_pipeline()
config = rs.config()

cfg.enable_stream(rs.stream.color, config, profile=0)
cfg.enable_stream(rs.stream.depth, config, profile=1)

# start streaming
pipeline.start(config)

# get the depth sensor scale
depth_sensor = profile.get_device().first_depth_sensor()
depth_scale = depth_sensor.get_depth_scale()

print('Depth Scale is:', depth_scale)

# create an align object
align = rs.align(config)

# MAIN PROGRAM

def main():
    # get global variables - variables that can be changed in main function
    global step_1, step_2, step_3, step_4, kpt_counter
    try:
        # start the main - Try
        while True
            # validate frame
            if not aligned_depth_frame or not aligned_color_frame:
                continue
            ir_left_frame = frames.get_infrared_frame()
            ir_right_frame = frames.get_infrared_frame()
            depth_image = aligned_depth_frame.get_data()

            color_image = aligned_color_frame.get_data()

            # intrinsics and extrinsics
            depth_intrin = depth_frame.profile.as_video_stream_profile().intrinsics
            color_intrin = color_frame.profile.as_video_stream_profile().intrinsics

            depth_to_color_intrin = depth_frame.profile.get_extrinsics_to(color_frame.profile)

            delta = 8

            if cv2.waitKey(1) == ord('k') or step_1 == True:
                print('test')
                step_1 = False
                cv2.setMouseCallback('Align Example', get_mouse_position)
                cv2.rectangle(color_image, (int(ch_pos[1][3]) - delta, int(ch_pos[1][3]) + delta),
                              (int(ch_pos[1][3]) + delta, int(ch_pos[1][3]) + delta), int(ch_pos[1][3]) + delta,
                              int(ch_pos[1][3]) + delta)
```
Finally, with the code being executed, the camera is ready to take the position of nodes. While the cameras are filming the actuator, nodes are selected. Selected nodes are represented by green squares shown by Figure D-2. The selected nodes have their 3D positioning recorded. Figure D-2 shows Camera 1 recording the position of certain nodes and Camera 2 (directly opposite from Camera 1) is recording the opposite nodes.
corresponding to the nodes captured by Camera 1. Using these values and coordinate transformation, the center node can be found.

Figure D-2: Cameras gathering data from both sides of the actuator. Camera 1 and Camera 2 are represented by the left and right figures respectively.

The camera and ABAQUSTM use different coordinate systems. The cameras read the following as positive directions: right (X-axis), down (Z-axis), and forward into the background (Y-axis). ABAQUSTM has positive directions: right (X-axis), down (Z-axis), and away from background (Y-axis). The only difference in the coordinate system is Y-axis. Figure D-3 and D-4 represent the camera and ABAQUSTM coordinate systems respectively. Once, all the experimental data have been gathered, the nodal positions from Camera 2 coordinate system should be transformed to the Camera 1 coordinate system and all data in Camera 1 coordinates should be transformed to the ABAQUSTM coordinate system. Finally, ABAQUSTM coordinate system should be transformed into the Right-Handed coordinate system.
Figure D-3: Camera coordinate system. Positive directions are right (X-axis), down (Z-axis), and forward into the background (Y-axis).

D-4: ABAQUS™ coordinate system. Positive directions are right (X-axis), down (Z-axis), and away from the background (Y-axis).
Appendix E

Actuator Motions and Views

The views of the actuator were not taken in the XY plane and YZ plane due to the difficulties in taking a picture of the actuator from underneath (XY plane). Also, for the YZ plane, there is no unique motion to capture from this plane. If the picture from the YZ plane was taken, then it would be similar to the pictures taken from the XZ plane. However, quantitative data from the nodes can provide an estimated look at how the soft actuator is supposed to look at a given pressure. The following are views of the actuator with tilt angles of 61° and 41° respectively from the XY plane (underneath the actuator). The views are represented by Figure E-1 and E-2. This view shows that coiling does take place. For the actuators with the tilt angles of 61° and 41°, the pressure is 12 psi and 9 psi for the following figures.

![Figure E-1: XY plane of the soft actuator with a tilt angle of 61°](image-url)
As shown by the previous figures, the actuators in the experimental and FEA models during pressurization begins to coil in the counterclockwise direction. Previously stated, from the top view of the actuator, the motion of the twisting is in the clockwise direction. This would mean that the direction from the bottom view would show the actuator twisting in the counterclockwise direction, which in this case it does. Observing Figures E-1 and E-2, the soft actuator appears to be coiling.
REFERENCES


