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Design and Testing of a Biomimetic Pneumatic Actuated Seahorse Tail Inspired Robot

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DESIGN AND TESTING OF A BIOMIMETIC PNEUMATIC ACTUATED SEAHORSE TAIL INSPIRED ROBOT

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
Justin Dakota Holt
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Accepted by:
Dr. Michael M Porter, Committee Chair
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ABSTRACT

The purpose of this study is to build and test a pneumatically actuated robot based on the biomimetic design of a seahorse tail. McKibben muscles, a form of pneumatic actuator, have been previously used to create highly flexible robots. It has also been discovered that the seahorse tail serves as a highly flexible and prehensile, yet armored appendage. Combining these topics, this research aims to create a robot with the mechanical flexibility of a pneumatic actuator and the protection of a seahorse tail. First, the performance of a miniature McKibben muscle design is examined. Then, the artificial muscles are implemented into a 3D-printed seahorse tail-inspired skeleton. The robot’s actuation was observed to determine its maximum bending capacities. The results of the experiments revealed that the miniature McKibben muscles performed comparably to larger sized McKibben muscles previously reported in literature. The pneumatically actuated robot achieved a maximum bend angle of ~22°. Further research is recommended to determine the behaviors of similar robots with additional plates or McKibben muscles spanning shorter plate sequences.
DEDICATION AND ACKNOWLEDGEMENTS

This thesis is dedicated to my parents, Arland Keith Holt and Catherine Danielle Holt. Their love and support has driven me through my collegiate life from my undergraduate degree in Physics to my furthered education in Engineering at Clemson University. In addition, I would like to thank my personal friend Lance Everhart for his support and help during my educational journey.

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I owe thanks to my research and lab partner Nakul R Kumar for his support and help during my research, as well as making the journey enjoyable and friendly as we progressed in our fields.
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1. INTRODUCTION

Nature can be considered a master of design. A prime example of its work is observed in the tail of a seahorse, which elegantly combines a capacity for prehension with armored protection (Porter et al. 2015). The motivation of this research is to create a robotic model of a seahorse tail for potential engineering applications, such as durable, highly flexible robotic limbs that can be utilized for manufacturing, medical tools, or search and rescue devices.

In engineering, an intended goal for many designers is to obtain an optimal method or process that performs a desired function or purpose. Humans have strived throughout their history to enhance and perfect their creations, be it from the hoe and plow to the current mass producing tractors and irrigators, or from simple hooks and wooden prosthetics to current robotic and mechanical limbs with amazing maneuverability. However, nature has long preceded our attempts of optimization through natural selection and adaptation. Nature has developed efficient flight through stiff, but lightweight bones with internal struts and ridges in birds (Currey 2002), or drag-reducing surfaces at high swimming speeds in sharks due to their skin’s dermal denticles (Bechert et al. 1985, Dean and Bhushan 2010). So, the question arises: Why should engineers reinvent the ingenuity of nature?

Organisms that develop adaptations best suited for survival live to pass on their genetic information—this is one basic concept of evolution. It can be compared to the design process in engineering; the best designs and ideas survive through the design process, which may change to incorporate new or added functions, producing more
favorable designs. Understanding this, engineers can take inspiration from natural designs and implement them into new engineering applications. Considered one of the first to explore this idea, D’arcy Thompson investigated several biological systems and structures from a mathematical point of view (Thompson 1917). He developed geometric models to explain the form of many common and convergent structures, such as the logarithmic spiral, which also happens to be the form of a curled seahorse tail.

Biomimetics looks to biology to recreate or mimic natural structures or functions, then apply them to meet various engineering needs. Recent developments, such as highly maneuverable search-and-rescue devices for the aftermath of natural disasters (Yim et al. 2000) or small controllable tools for surgical procedures (Gharagozloo and Najam 2009), have sparked a renewed interest in serial robotics. In many instances, such as exploration in rubble, serial robots should also be impact and crush resistance. That is the objective of this research: to develop a highly-maneuverable robot with added protection against impact and crushing.

Nature has already developed such a flexible, armored structure in the form of the seahorse tail (Hale 1996). Fishes of the genus *Hippocampus*, which includes seahorses, have a unique musculoskeletal structure that allows them to grasp with their tails, which are highly maneuverable appendages despite a heavy armored plating (Hale 1996, Praet et al. 2012, Neutens et al. 2014). Their skeletal structure also allows the tail to withstand transverse compressive forces (Porter et al. 2013). Thus, the development of a physical model to better understand the mechanical design of a seahorse tail could inspire similar structures for applications requiring both prehension and protection (Porter et al. 2015).
In this research, a seahorse tail-inspired robot composed of mechanically similar 3D-printed bones and artificial muscles was developed. The skeleton of the robot was redesigned from previous work (Porter et al. 2015) and outfitted with pneumatically-powered actuators, commonly known as McKibben muscles (Chou and Hannaford 1994). The McKibben muscles were chosen because of their relatively simple, lightweight and flexible design, safe operation and small size when compared with other actuators, including servo-motors (Wright et al. 2007, Marvi et al. 2014), electro-active and shape-memory materials (Calisti et al. 2011, Laschi et al. 2012), or mechanically-driven cables and tendons (Li and Rahn 2002, Camarillo et al. 2008). McKibben muscles are constructed from an expandable tubing constrained in one dimension by a mesh sleeving that forces the actuator to contract much like a biological muscle (Gaylord 1958). In general, pneumatic actuators are quite diverse, but for biomimetic applications, McKibben muscles are popular in research because they closely simulate the uniaxial actuations of single muscle fibers (Chou and Hannaford 1994). Using these pneumatically-powered muscles and a 3D-printed skeleton, the kinematic maneuverability observed in the seahorse-inspired robot was explored. 3D printing was employed to build a simplified, yet biologically representative skeletal structure, following an established procedure (Porter et al. 2015); but, it was modified to house the McKibben actuators. The robot will be used in future work to examine the kinematic and mechanical behaviors of its biological inspiration, the seahorse tail.
2. ANATOMY OF A SEAHORSE TAIL

2.1 SKELETAL STRUCTURE OF A SEAHORSE TAIL

A seahorse tail consists of several repeating segments of L-shaped, bony plates arranged into a square ring-like overlapping fashion (Hale 1996). These plates are connected by several unique joints with varying degrees of freedom and surround the tail’s central vertebral column (Praet et al. 2012, Porter et al. 2013, Neutens et al. 2014). Not only do they allow for excellent flexibility and maneuverability, they also protect against predatory threats (see Figure 1) (Porter et al. 2015).

![Image of a seahorse](image1.png)

**Figure 1. The seahorse.** (Left) An image of a seahorse with its dorsal, anterior, ventral and posterior areas labeled. Taken from (Porter et al. 2013); (Right) Micro-computed tomography images of a seahorse and its tail bending and twisting, and crushing. Taken from (Porter et al. 2015).

Prehension is the ability of an appendage to grasp and hold an object. An example is the human hand (Napier 1956). To be considered prehensile, an object, either fixed or
free, should be held securely. The seahorse tail is prehensile due to its ability to grasp objects, such as coral and submerged foliage. It typically anchors itself onto aquatic vegetation to blend into its surroundings through camouflage, allowing it capture prey by a sit-and-wait suction feeding strategy (Gemmell et al. 2013). This makes seahorses unique among their aquatic brethren, since they (and pipehorses) are some of the only known prehensile fishes.

The resistance to transverse deformation and compressibility of a seahorse skeleton has also been investigated (Porter et al. 2013, Porter et al. 2015). It was found that the unique square shape and overlapping joints allow the seahorse tail to withstand compression of ~50% of its original width without sustaining permanent deformation of its vertebral column. The bony plates consist of a micro-hardness of 230 ±80 MPa (Porter et al. 2013), which is much lower than that of comparative bovine femur bones, which range from 550 to 700 MPa (Currey 2002). The relatively deformable nature of the bones as well as the unique overlapping joints that connect each plate, results in the tail exhibiting a relatively high strain to failure when compared with a similar square-ring structure containing no joints (Porter et al. 2015).

As seen in Figure 2, the tail consists of ~30-40 square ring segments, each defined by four corner plates. These plates, and hence the segments, decrease in size linearly down the length of the tail. The vertebra of each segment forms a cross along the lateral and ventro-dorsal directions of the tail, where four strut-like extensions are connected to the overlapping plates. The bony plates, along with the vertebrae, make up eight translational joints and five rotational joints per segment (Praet et al. 2012, Porter et al. 2013).
Overlapping joints at the ring mid-sections and peg-and-socket joints at the ring corners allow the plates to slide past one another with approximately one translational degree of freedom. Ball-and-socket joints along the vertebral column and pivoting joints at vertebral strut-plate interface allow the tail to bend with approximately three rotational degrees of freedom. Collagenous connective tissues also permit some minor degrees of freedom in rotation and translation when the joints slide and rotate, respectively.

Figure 2. The skeletal structure of a seahorse tail. (Top) A micro-computed tomography image of whole seahorse tail skeleton composed of several segments of bony plates surrounding a vertebral column. Adapted from (Praet et al. 2012); (Bottom) (a-b) A diagram and micro-computed tomography image of the plate and vertebra arrangement; (c-f) micro-computed tomography images of the different joints found in each segment. Taken from (Porter et al., 2013).
2.2 MUSCLE STRUCTURE OF A SEAHORSE TAIL

In addition to connective tissues, muscles connect the bony plates to the tail’s vertebral column (Praet et al. 2012, Neutens et al. 2014). Figure 3 shows the typical muscular arrangement in a seahorse tail. The muscle fibers, myotomes and myomeres, are connected to myoseptal sheets arranged into W-shaped and parallel patterns. Median ventral muscles also run between adjacent vertebral struts. During prehensile activities, the myotomes and myomeres contract pulling the myosepta together, which in turn apply a force from the vertebrae to the bony plates. This allows the plated tail to bend and twist in a wide array of motions.

Figure 3. The muscular structure of a seahorse tail. (Left) Micro-computed tomography images of the hypaxial myomere muscles (HMMs) and median ventral muscles (MVMs). Taken from (Praet et al. 2012). (Right) Schematic diagram of the conical and parallel myoseptal sheets found in the dorsal and ventral quadrants of the seahorse tail, respectively. Taken from (Neutens et al. 2014).

While the general structure of the muscles has been recently elucidated (Praet et al. 2012, Neutens et al. 2014), little is known about their exact anatomical functions. In particular, most fish species contain the more common W-shaped myosepta structure, which is also found along the dorsal side of the seahorse tail. The cone-like arrangements
of myoseptal sheets allows the muscle fibers to pull adjacent segments together (Van Leeuwen 1999). In contrast, the parallel sheet-like structures on the ventral side of the tail are not as common among fishes. This arrangement connects one segment to another approximately seven rings down the length of the tail. The muscle fibers are aligned at an angle between adjacent myoseptal sheets. When the fibers contract, they pull the parallel sheets together causing the myosepta move at angle along the vertebrae anchored to the dermal plates. Although not previously investigated, this musculoskeletal structure likely allows the seahorse tail to bend and twist to a much greater degree that other fishes that use their tails for swimming via undulation. Therefore, the seahorse tail-inspired robot designed and built in this study could be further applied to better understand the functions of the different muscular arrangements.

2.3 PREHENSILITY VERSUS UNDULATION

Undulation, in its simplest definition, is a wave-like motion. It is a mechanically efficient form of locomotion in many aquatic animals with elongated bodies. This motion is achieved by a unique myomere-myosepta structure present in the bodies of many fishes. Axial myomere tendons and transverse myoseptal tendons in a fish’s body produce large forces through the tail. Mechanically, the vertebrae can be treated as beam-like structures with hinge connections (see Figure 4), where the axial myosepta and muscle structures act as dampers and springs (Long et al. 2002). In seahorses, the musculoskeletal structure is similar to other fishes in the dorsal quadrants, but very different in the ventral quadrants where their hypaxial myomere muscles are arranged into parallel sheets as previously
It is not yet fully understood why these muscles are arranged in such a way. But it has been hypothesized that their unusual muscle structure is related to their prehensile capacity (Hale 1996, Praet et al. 2012, Neutens et al. 2014). Even though the seahorse does not use its tail for swimming, it possesses as much or more maneuverability than other fishes. It is thought that the parallel muscles (hypaxial myomere muscles) are utilized for the quick bending motions while the conical ones (median ventral muscles) are utilized for sustained bending such as the holding of an object (Hale 1996). This allows the seahorse to make use of the high degree of freedom most fish use for undulated motion for prehension.

**Figure 4. Spinal muscle function.** Taken from (Long et al. 2002): “Muscle force is a vector quantity (thick black arrow) acting at a distance, $a$, from the joint and parallel to the anterior vertebra (green) in the series. That force generates a moment via the moment arm (dashed line) from the point of action and the centroid of the posterior vertebra (blue) in the series. This structure transmits forces from local and adjacent segments to the myosepta.”
3. PNEUMATIC ACTUATION IN SERIAL ROBOTICS

Pneumatic actuators come in a variety of configurations. In general, they are composed of a membrane that can be pressurized, causing them to deform along pre-defined paths dependent on the various channels or reinforcements that constrain their motion. They can be categorized as membrane actuators, bellow actuators, balloon actuators, or artificial muscles, as outlined in Figure 5 (De Volder and Reynaerts 2010).

Figure 5. Types of pneumatic actuators. A range of pneumatic based actuators including the membrane type, the balloon type, the bellow type, and artificial muscle. Taken from (De Volder and Reynaerts 2010).
3.1 MEMBRANE AND BELLOW ACTUATORS

Membrane actuators are one of the most basic and common forms of pneumatic actuators (De Volder and Reynaerts 2010). The actuator is categorized by its membrane-like design. They consist of thin, flat or corrugated membranes, generally with spaced cells along the interior of the membrane. When supplied with a driving pressure the cells inflate causing the membrane to deform or bend along the side of the cells with the greatest compliance. Such actuators can grasp objects as they deform in a single direction and wrap around the object (Ok et al. 1999). These actuators are known for their ease of fabrication and were made popular in the late 1980s (Van De Pol et al. 1989). The elastic materials, flexible silicone rubber, used to create the actuators capitalize on the material’s low Young’s modulus (Unger et al. 2000), but generally suffer from the actuators low stroke length, or small area of deformation, compared to other pneumatic actuators.

Bellow actuators are a similar type of pneumatic design and consist of an elevated cell that expands in a single direction (De Volder and Reynaerts 2010). These actuators have a relatively high stroke length, and were first conceived in 1997 (Yang et al. 1997). Much like membrane actuators, bellow actuators may be useful for a variety of medical instruments such as catheters or forceps (De Greef et al. 2009).

3.2 BALLOON ACTUATORS

Balloon actuators are like membrane actuators, except that the cells used to perform the deformation are larger, resulting three-dimensional deformations that resemble the appearance of a balloon (De Volder and Reynaerts 2010). Upon inflation, the balloons
produce a higher tensile stress on one surface than the other, resulting in a contraction and corresponding bending of the structure on one of its sides. **Figure 6** shows the bending response of two different balloon-type actuators. In one type (**Figure 6a**), the actuator material is homogeneous; when inflated, it causes concave or convex bending, depending on the membrane geometry and material. One of the first uses of this type of actuator was to mimic the bending function of a spider’s leg (Parry and Brown 1959). Similar actuators were also implemented into micro electrical mechanical systems (Schwörer et al. 1998), and further improved using silicone (Konishi et al. 2001). In another type (**Figure 6b**), the actuator is composed of two materials of different stiffness, in which the stiffness ratio controls the actuator in a more consistent manner. These actuators have been used to create finger-like models (Jeong et al. 2005), and show promise for biomedical tools due to their high range of motion and control (Okayasu et al. 2003).

**Figure 6. Balloon actuators.** (a) An actuator made of a uniform, homogenous polymer; (b) a actuator made of two layered polymers of different stiffness, where the top material (A) is stiffer than bottom one (B). [i-iii] (a) shows that a uniform actuator will deform in the direction of the thinner layer until a point where the thicker layer will cause the actuator to bend in reverse; (b) shows that a layered polymer with the stiffer material on top will cause the actuator to bend upwards. Taken from (Konishi et al. 2001).
More recently, other types of balloon actuators have become popular in research; examples include pneu-nets (Ilievski et al. 2011) and soft robotic tentacles (Martinez et al. 2013). Pneu-nets, or pneumatic networks, consists of repeating channels embedded in series in an elastomeric substrate (Ilievski et al. 2011). Similar to previous designs, the channels inflate like balloons when pressurized. The repeated channels cause the segments to inflate, push against one another, and deform per their geometries. More complex geometries allow the actuators to exhibit a variety of motions. The actuation rates can also be increased by incorporating relief zones between cells (Mosadegh et al. 2014). Figure 7 shows examples of some pneu-net actuators.

**Figure 7. Pneu-nets.** (Left) Designs of pneu-nets with cellular membranes for (A) slow and (B) fast actuation. Taken from (Mosadegh et al. 2014). (Right) Pictures of several different pneu-net actuator designs. Taken from (Ilievski et al. 2011).
Another form of balloon actuators are soft robotic tentacles (Martinez et al. 2013). The tentacles function in a similar manner to pneumatic nets, but are instead constructed with inflatable channels that are aligned parallel to their central axis. This parallel orientation allows the system to achieve higher degrees of freedom and more complex deformations than their predecessors (Martinez et al. 2013). However, the actuators are generally more difficult to control. Figure 8 shows an example of a tentacle-like pneumatic actuator.

Figure 8. Soft robotic tentacles. (a) Design and air delivery system. (a) Deformation of a tentacle cross-section when a single chamber is inflated. (c) Deformation of a tentacle when a single chamber is actuated. Taken from (Martinez et al. 2013).
3.3 MCKIBBEN MUSCLES

McKibben muscles are the type of pneumatic actuator used in this research. McKibben muscles, also called artificial muscles or pneumatic muscle actuators (PMAs), are unique among the pneumatic actuator family. The first example of this method was introduced by Pierce via patent in 1936 (Pierce 1940). Originally, the patent was intended to be used in the mining industry, using the bladder’s radial expansion to apply force to coal and eventually break it loose, as an alternative to dynamite. Thirteen years later De Haven filed a patent for a similar device using a double helical mesh pattern (De 1949); however, it focused on a lateral contraction instead of a radial expansion. Another patent was filed in 1958 by Gaylord for a similar design (Gaylord 1958). He derived calculations for the actuators’ theoretical contractive force based on its fibers relaxed angular orientation, relaxed and inflated diameter, and applied air pressure within the bladder.

However, it was not until 1962 that the device received its often used moniker, the McKibben muscle, when Joseph McKibben published a paper detailing the device’s possible implementation into prosthetic devices and furthered mathematical analyses based on Gaylord’s previous work (Schulte 1961). However, due to the era’s limitations for accurate pneumatic controls and obtuse power sources it was not further developed (Davis et al. 2003). Later, these artificial muscles saw commercial use in the 1980s when Bridgestone sought to include them in industrial robots. They dubbed the devices Ribbertuators and implemented them into two robots, the RASC and Soft Arm (Inoue 1988). The robots saw use for a few years before being discontinued in the 1990s (Davis et al. 2003).
McKibben muscles hold many benefits in terms of practical and theoretical usage. They can be built in many variable sizes from over a meter in length, down to a diameter of 1.5mm and 22mm in length (De Volder et al. 2008). The muscles also have high power-to-weight ratios in comparison to their electronic based counterparts and power-to-volume ratios (Liu et al. 2015). Additionally, they pose a low level threat during operation when compared to electric motors or hydraulic actuators generally seen in manufacturing and robotics (Caldwell et al. 1995).

These artificial muscles are characteristically defined by their inner expandable bladder constrained by an exterior mesh (De Volder and Reynaerts 2010). When the bladder is pressurized, it expands in diameter much like a balloon. However, the meshing balances the internal pressure of the tubing through tension of the fibers. This, in turn, causes the fibers to change angle as the bladder increases in diameter, causing the muscle’s effective length to shorten and contract (Daerden and Lefeber 2002). A simple diagram of the muscle’s contractive action is shown in Figure 9. Such an actuator has even been used in tandem with other McKibben muscles to emulate the flexibility of an elephant trunk with multiple muscle segments (McMahan et al. 2006). The segments consisted of three grouped McKibben muscles which can alternately actuate to produce a contraction in different direction while the others remain inactive (see Figure 10). This allows the robot to actuate several non-paired muscles along the length of the segmented plate structure to obtain a high degree of maneuverability.
Figure 9. McKibben muscle. (A) Cross-section of a McKibben muscle including its mesh sleeving and elastic bladder. (B) Change of fiber angle as the muscle actuates. Taken from (De Volder et al. 2011).

Figure 10. The Octarm. The maneuverability of paired McKibben Muscles in Clemson University’s Octarm. The McKibben muscles are grouped in a series of three. When actuated a McKibben muscle contracts allowing the robot to deform in the direction of the side of that muscle. Taken from (McMahan et al. 2006).
McKibben muscles are uniquely applicable to engineering and biology disciplines, as they closely mimic the function and performance of natural muscle (Chou and Hannaford 1994). Mathematical models to predict their performance and behavior are presented below. Figure 10 shows a diagram of a McKibben muscle, illustrating the different parameters used to characterize its structure. Their geometric design is described as (Liu et al. 2015):

\[ L = b \cos \theta \]  
\[ D = \frac{b \sin \theta}{n\pi} \]

where \( L \) is the overall length of the actuator, \( b \) is the length of one strand of the meshing and \( \theta \) is the angle of the fiber. \( D \) is the diameter of the McKibben muscle and \( n \) is the number of times the fiber encircles the muscle from end cap to end cap. The contractive force can be approximated as:

\[ F = \frac{\pi D_0^2 P}{4} (3 \cos^2 \theta - 1) \]

where \( D_0 \) is the diameter of the muscle if the fiber angle of the meshing is at 90°, its theoretical maximum, and \( P \) is the pressure (Schulte 1961). This model was first introduced by Gaylord in order establish a relation between the fluid pressure when the actuator was in use and the contraction force achieved by its actuation (Gaylord 1958). It was later discovered that the angle from a theoretical 90° would only contract to a braid angle of 54.7°. This created an error of 15-20% between the modeled prediction and measured experimental observations (Davis et al. 2003). The formula below is a corrected model
used to account for the effects of friction between the rubber bladder and meshing (Chou and Hannaford 1994):

$$F = \frac{\pi D_0^2 P}{4} (3 \cos^2 \theta - 1) + \pi P \left[ D_0 t_k \left( 2 \sin \theta - \frac{1}{\sin \theta} \right) - t_k^2 \right]$$

(4)

where $t_k$ is the thickness of the braided meshing. This model was introduced to incorporate a corrective force introduced by friction by the fibers on the bladder. However, even with this correction, errors of up to 15% were still seen in some tests (Chou and Hannaford 1994).

Alternatively, following the conservation of energy, $W_E = W_S + W_F + W_C$, the apparent elastic modulus of a composite McKibben actuator can be derived (Liu et al. 2015):

$$W_E = E \pi (D_0 - w_0) w_0 \left[ L_0 \ln \left( \frac{L_2}{L_1} \right) + L_1 - L_2 \right]$$

(5)

$$W_S = \pi p L_2 \left( \left( \frac{b^2 - L_2^2}{2 \pi n} - \frac{D_0 L_0 w_0 \pi}{2 L_1 \sqrt{b_1 - L_1^2}} \right)^2 - \left( \frac{b^2 - L_2^2}{2 \pi n} - \frac{D_0 L_0 w_0 \pi}{2 L_1 \sqrt{b_1 - L_1^2}} \right)^2 \right)$$

(6)

$$W_F = F (L_2 - L_1)$$

(7)

$$W_C = \pi \pi r_0^2 (L_2 - L_1)$$

(8)

where $E$ is the elastic modulus of the mixed bladder, $w_0$ is the initial thickness of the muscle, $L_0$, $L_1$ and $L_2$ are the lengths of the muscle, initially, and in state 1 and state 2, $p$ is the given pressure, and $F$ is the contractive force.
Figure 11. McKibben muscle diagram. A visual example of the variables used to calculate the performance of a McKibben muscle where $D$, and $D_i$ are the outer and inner diameters respectively, $n$ is the number of times a fiber encircles the length of the muscle, and $b$ is the length of a single fiber of the braided meshing. $w_1$ and $w_2$ define the muscle's thickness when at rest and actuated, $D_1$ and $D_2$ are the diameters of the muscle at rest and actuated respectively, $L_1$ is the initial length, $L_2$ the actuated length, and finally $F_1$ and $F_2$ are the forces generated by the muscle. Taken from (Liu et al. 2015).
4. MATERIALS AND METHODS

4.1 MATERIALS

Below is a list of materials used to build the muscles and skeleton of the robot:

**Muscles:**
- 10.67 mm needle blow gun tip (SNT-1, Coilhose Pneumatics, East Brunswick, NJ)
- 3.18 mm ID, FLEXO expandable polyester sleeving (Techflex, Sparta, NJ)
- 0.79 mm ID, high-temperature silicone rubber tubing (McMaster-Carr, Atlanta, GA)
- 11.43 mm D, black 3-1 heat shrink with inner adhesive (McMaster-Carr, Atlanta, GA)
- 4.76 mm D, clear 2-1 heat shrink with inner adhesive (McMaster-Carr, Atlanta, GA)
- Custom plugs printed on a Connex500 Polyjet 3D-printer (Stratasys, Eden Prairie, MN)

**Skeleton:**
- Modified 3D-printed plates and vertebrae, based on (Porter et al. 2015) and printed on a Connex500 Polyjet 3D-printer (Stratasys, Eden Prairie, MN)
- 1.0 mm D, elastic cord (Bead Landing™, Michaels, Irving, TX)
- 8.0 mm D, glass beads (Bead Landing™, Michaels, Irving, TX)
- 0.5 mm D, monofilament fishing line (Berkle, Columbia, SC)

4.2 CONSTRUCTION OF THE MUSCLES

*Figure 12* shows images of the materials used to construct the McKibben actuators. First, the polyester sleeving and silicone rubber tubing were cut to lengths of ~175 mm, leaving extra slack to adjust the muscle length when applying the end cap during assembly. Next, two segments of 2-1 heat shrink were cut to a length of ~45 mm and ~15 mm, respectively, making sure that one was longer than the needle so that the bladder would not be punctured during inflation. Next, the needle was inserted into the silicone tubing, which
was encased by the FLEXO sleeving, and sandwiched together with the heat shrink, then secured with 10 mm zip ties. The larger 3-1 heat shrink was then fit onto the entire assembly, including the base of the needle to prevent leaks and keep the muscle from slipping off the needle during actuation. Finally, before securing the end cap (plug), it was test-fit into the silicon tubing so that the muscles could be measured to the appropriate length of 127 mm for unrestricted contraction. To cap the muscles, the 2-1 heat shrink was secured to the free end with some overhang to prevent the plug from slipping during inflation. **Figure 13** shows various steps during the muscle’s construction.

![Figure 12. McKibben muscle materials.](image)

The materials needed to construct a McKibben muscle are (1) an expandable bladder, (2) a mesh sleeving, (3) an air needle, (4-6) heat shrink, (7) a plug, (8) zip ties.
4.3 CONSTRUCTION OF THE SKELETON

The 3D-printed skeleton was based off previous work (Porter et al. 2015), as shown in Figure 14. The model used in this research used a similar plate and vertebrae design, except that guide holes were included through the square plates and vertebrae to accommodate the McKibben muscles at specified locations.
Figure 15 shows images of the parts used to construct the 3D-printed skeletons. Seven sets of four plates and one vertebra per segment were modified from an original model (Porter et al. 2015) using a computer-aided design software (SolidWorks, Dassault Systemes, Waltham, MA) and printed in VeroWhite® material with a Connex 500 Polyjet 3D-printer (Stratasys, Eden Prairie, MN). Figure 16 shows various steps during the skeleton’s construction. The plates and vertebrae were held together with elastic cords strung through the center of the assembly, mimicking the connective collagen tissues of the natural joints. Glass beads served as the ball-and-socket joints between vertebra, which were held together with fishing line. The low coefficient of friction of the glass beads and high tensile strength of the fish line allowed the model to bend and twist with ease, without expanding apart. When assembling the seven segments together, the overlapping plates on opposing ends of the vertebrae were alternated, forming a quadrilateral symmetric (clockwise-anticlockwise…) pattern with the proximal segment overlapping in a clockwise direction. The proximal ring of the assembly was then affixed to a solid plate-vertebra segment with no overlapping joints; this allowed the robot to be securely connected to an air supply, and prevented the base plate from moving during actuation. Next, the inlets of four McKibben actuators were inserted into guide holes at the corners of the solid plate-vertebra ring. The other, free ends of the four McKibben actuators were secured into guide holes on the vertebra, seven segments down at the distal tip. The guide holes served as pseudo-connection points analogous to the points where muscles would anchor between the plates and vertebrae in a natural seahorse. It is important to note that the actuators were only partially constructed before inserting them into the skeleton, such their free ends could
be capped and properly fitted into the vertebral guide holes. Figure 17 shows images of the completed seahorse tail-inspired robot composed of a white 3D-printed skeletons and orange McKibben muscle actuators.

Figure 15. Skeleton materials. (1) The solid plate-vertebra part, which anchored the articulated skeleton to the testing apparatus; (2) a 3D-printed vertebra and (3-6) four 3D-printed plates with guide holes to fit the muscles; (7) an 8mm glass bead, and (8) elastic cord.

Figure 16. Building the robot skeleton. (Top) Threading the plates and vertebrae together with elastic cord and fishing line. (Bottom) Inserting the actuators into the base (left) and free end (right) of the skeleton.
4.4 ACTUATION AND TESTING

An in-house air supply was connected to four SMC ITV1050-31N1N4 regulator pumps (SMC Pneumatics, Yorba Linda, CA) to control the supplied pressure to each muscle between 0 and $\sim 520$ kPa. The regulators were controlled with a Quanser Q8-USB data acquisition board (Quanser, Markham, Ontario, Canada) and run by the company’s Simulink program in Matlab. The maximum pressure for each test was set to $\sim 520$ kPa and applied at several different actuation rates. Figure 18 shows pictures of an SMC regulator pump, Quanser board, and a screenshot of the Quanser control software.
During actuation, the robot was recorded with a Nikon D5100 digital camera. Videos were analyzed by converting them to still images at specified time intervals. Each image was examined to determine the position of the center of the black elastic cords on each of the six segments, which were treated as nodes in a 2D-plane with \((x, z)\) coordinates. Figure 19 displays the coordinate system. The pixel locations of each node were converted to their corresponding location in millimeters to determine their relative displacements with respect to the origin (at the proximal center of the robot) and the start of the actuation sequence (at zero seconds). The bending angles of each segment were calculated from the relative displacements \((x, z)\) of each node into the first quadrant (see Figure 19):

\[
\phi = \tan^{-1}\left(\frac{x_1 - x_2}{z_1 - z_2}\right) * \frac{180}{\pi}.
\] (9)

In addition, the McKibben muscles were tested individually before insertion into the robot skeleton. To do this, the inlet needle was secured to a plane surface using a C-clamp, as shown in Figure 19. To ensure the assembly did not move during testing, the positions of the clamps were recorded before and after each test. Two experiments were conducted on a total of nine individual muscles, three at each length of 127 mm, 63.5 mm,
and 31.75 mm. The contraction length and force of each muscle was recorded at increments of ~35 kPa, up to a maximum pressure of ~520 kPa. For measurements of the contraction length, the muscles were housed in clear plastic tubes to limit their out-of-plane bending; initial and actuated lengths were measured with digital calipers as well as video images using ImageJ software (National Institutes of Health). For measurements of contraction force, a metal eyelet was secured to the free-end of the muscle and hooked to a Shimpo FGV-50XY force gauge (Shimpo Instruments, Cedarhurst, NY), as shown in Figure 19.

Figure 19. Robot and muscle testing. (Left) Image of the robot bent to an angle of 22° at a maximum actuation pressure of ~520 kPa. (Right) Contraction force testing setup for a standard McKibben muscle.
5. RESULTS AND DISCUSSION

5.1 MCKIBBEN MUSCLES

The McKibben muscles contracted >25% and produced >40 N when actuated up to ~520 kPa, which is comparable to the behaviors of larger McKibben muscles (Chou and Hannaford 1994). Figure 20 shows the measured contraction force (N) and length (%) at different pressures versus the theoretical contraction force predicted by Equation 4:

\[
F = \frac{\pi D_0^2 P}{4} (3 \cos^2 \theta - 1) + \pi P \left( D_0 t_k \left( 2 \sin \theta - \frac{1}{\sin \theta} \right) - t_k^2 \right)
\]

where \( D_0 = 0.00865 \text{ m} \) for the maximum diameter of the muscle if the fibers were at 90°, from the equation \( D_0 = \frac{b}{n \pi} \), \( b = 0.13589 \text{ m} \) is the length of an individual fiber, \( n = 5 \) for the number or times a single fiber wraps around the entire of muscle, \( P = 517.107 \text{ kPa} \) for the maximum pressure, \( \theta = 20° \) for the braid angle, and \( t_k = 0.00025 \text{ m} \) for the fiber width. Accordingly, it is estimated that the muscle should be able to obtain a contraction force of 42.14 N, which is within 6% of the recorded maximum (see Figure 20).

Figure 20. McKibben muscle actuation results. The average ± standard deviation of the contractive force (purple dots ± error bars) and length (orange dots ± error bars) of the McKibben muscles compared with the theoretical force calculated by Equation 4 (solid purple line).
5.2 SEAHORSE TAIL INSPIRED ROBOT

The seahorse tail-inspired robot tests were conducted in a two-dimensional plane only. To achieve planar bending, two adjacent muscle quadrants were actuated simultaneously, forcing the first and seventh segments to contract towards one another. Figures 21-22 show the 2D displacement measurements during a single contraction and release event. Figure 21 displays the $x$ and $z$ positions of the center node of each segment in the 2D plane. The locations of each node were measured relative to the pixels’ $x$ and $z$ positions at each time frame. The colors on the plots correspond to the testing times, where darker colors represent earlier times and lighter colors represent later times. Figure 22 shows the $(x, z)$ coordinates of each node where the time scale also progresses from dark to light. As seen in these plots, the distal-most nodes (fifth-seventh) bent away from the central axis into the first quadrant upon actuation up to a maximum pressure of $\sim 520$ kPa. Interestingly, however, the third and fourth vertebrae exhibited a “kick-back” behavior, translating away from the central axis in the opposite direction of actuation. In all, this behavior resulted in a total bend angle of $21.495^\circ$, as measured from its original vertically hanging position (see Figure 19).

In comparison, the 3D-printed skeleton without internal actuators exhibited a passive bending capacity of $\sim 40^\circ$ over an equivalent span of seven segments, nearly double its actuated capacity of $\sim 22^\circ$. This shows that while the McKibben muscles force the skeletal structure to contract in a similar manner as the biological muscles of a seahorse, they do not permit a full range of motion as constrained by the skeleton. A possible explanation for this discrepancy is that the unactuated muscles at rest are inextensible.
Thus, they pull against the seventh distal-most vertebra and push against the vertebral column on the convex side during bending, limiting the robot’s range of planar motion (see Figure 22). To reduce these effects, the non-actuated muscles could be removed or lengthened, but at the cost of eliminating or reducing their contractive action for bending in the opposite direction. Furthermore, the “kick-back” behavior observed in the third and fourth segments may be a result of interference between the inextensible muscles and vertebral column. Because the muscles cannot pass through the vertebral struts, they forced the middle segments to deflect in the opposing direction, which permits an increase in the robot’s total curvature.

![Figure 21. Node displacement.](image)

Plots showing each of the six nodes’ \( z \) (left) and \( x \) (right) positions over an actuation of 125 seconds, up to \( \sim 520 \text{ kPa} \). The color scheme indicates the progression of time; darker colors are earlier times and lighter colors are later times.
To verify these conjectures, the robot was actuated at several different rates up to its maximum capacity of ~520 kPa. Figure 23 shows plots of the bend angles versus actuation times at the different rates. It was found that when actuated at ~520 kPa/sec, the maximum bend angle achieved by the robot was 20.592°. When actuated at lower rates down to ~5 kPa/sec, however, the maximum bend angle achieved was 21.495°, which was the observed static capacity. Thus, it is concluded that when the robot is actuated at slow rates, the plates slowly slide past one another and “settle” into an optimal bent position. In contrast, near-instantaneous actuations (>500 kPa/sec) seem more restrictive, likely because of friction between plates at the peg-and-socket joints and the inextensible muscles with the vertebral column.
Figure 23 also shows a plot of the actuation rates versus bending rates for the robot, taken as the slopes of the curves from 0-20% of the actuation times. For comparison, contraction rates for the individual muscles were also measured, corresponding to the data presented in Figure 20. Clearly, both the robot (bending versus actuation rates) and individual muscles (contraction versus actuation rates) exhibit nearly linear power-law behaviors. Therefore, the bending response of the robot actuated at different rates primarily depends on the response of the muscles, but not as much on the design of the 3D-printed skeleton.

Figure 23. Actuation rates. (Left) Plot of the robot bending angle versus actuation time for ~500 kPa/sec (red), ~100 kPa/sec (yellow), ~20 kPa/sec (green), ~10 kPa/sec (blue), and ~5 kPa/sec (purple). (Right) Log-log plot of the bending rate (degrees/sec) and contraction rate (% length/sec) versus actuation rates (kPa/sec) for the robot (black) and an individual muscle (orange), respectively.
5.3 KINEMATIC MODELING

From the bending experiments, it was observed that each ball-and-socket joint bent at different angles and rates, causing the first few segments to move away from the central axis (see Figure 22). Thus, linear algebra was employed to help model this behavior and predict the bend angle at each ball-and-socket joint for any arbitrary number of segments. In addition, the model was used to determine the optimal muscle length for a seven-segmented 3D-printed skeleton.

Here, matrices represent the 2D locations of each vertebral node, which were approximated as the central positions of the black elastic bands, as shown in Figure 22. Refer to Figure 24 for a frame of reference. Using a translation matrix, the \((x, z)\) position of a node with respect to the distance, \(L\), between adjacent segments is:

\[
\begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & L \\
0 & 0 & 1
\end{bmatrix} \cdot \begin{bmatrix} x \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ z + L \\ 1 \end{bmatrix}
\] (10)

which translated the point \((x, z, 1)\) by an length of \(L\) on the Cartesian plane. Accounting for the angle of rotation, \(\theta\), between adjacent segments, the position of a node is:

\[
\begin{bmatrix}
cos\theta & sin\theta & 0 \\
-sin\theta & cos\theta & 0 \\
0 & 0 & 1
\end{bmatrix} \cdot \begin{bmatrix} x \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} xcos\theta + zsin\theta \\ zcos\theta - xsin\theta \\ 1 \end{bmatrix}
\] (11)

which rotates the point \((x, z, 1)\) clockwise \(\theta\) degrees on the Cartesian plane. Next, each segment is examined as a transformation in \(\mathbb{R}^2\) space. For the first base segment, which is statically anchored, its central node is defined as:

\[
\begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & L_n \\
0 & 0 & 1
\end{bmatrix} \cdot \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}
\] (12)
where $L_i$ is the length between the nodes of the $i$-th segment and the $(i - 1)$th segment. However, if $i = n$, it represents the length of the first fixed segment, which serves as the static base of the robot. With respect to the base, the second segment’s node is positioned a distance $L_{n-1}$ and rotates clockwise an angle $\theta_{n-1}$. Therefore, the position of the second segment is defined as:

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & L_n \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos \theta_{n-1} & \sin \theta_{n-1} & 0 \\ -\sin \theta_{n-1} & \cos \theta_{n-1} & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 0 \end{bmatrix}. \quad (13)$$

If iterated up to $i = m$ where $m$ is between 1 and $n$, such that $n$ represents the total number of segments and 1 represents the distal-most segment, the overall positions of the nodes can be written as:

$$\left( \prod_{i=m}^{n} \begin{bmatrix} \cos \theta_i & \sin \theta_i & 0 \\ -\sin \theta_i & \cos \theta_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \right) \cdot \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 0 \end{bmatrix}. \quad (14)$$

which results in a vector:

$$\begin{bmatrix} x_m \\ z_m \\ 1 \end{bmatrix}. \quad (15)$$

Thus, a segment’s displacement can be measured by Pythagorean’s theorem in $\mathbb{R}^2$ space:

$$\Delta d_m = \sqrt{x_m^2 + (\Sigma_{i=m}^{n} (L_i - z_m))^2}. \quad (16)$$

Now, let $L_l$ be the length between the left side of the first and last segments, $L_r$ be the length between the right side of the first and last segments, and $L_c$ be the length between the center of the first and last segments (see Figure 24, center image). Also, let $w$ be the width of the segments; then, with $n$ segments, Equation 14 can be rewritten as:
\[
\begin{pmatrix}
\cos \theta_i & \sin \theta_i & 0 & \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & L_i \end{bmatrix} \end{pmatrix} \cdot \begin{bmatrix} -w/2 \\ 0 \\ 1 \end{bmatrix}
\]
\quad (17)

and

\[
\begin{pmatrix}
\cos \theta_i & \sin \theta_i & 0 & \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & L_i \end{bmatrix} \end{pmatrix} \cdot \begin{bmatrix} w/2 \\ 0 \\ 1 \end{bmatrix}
\]
\quad (18)

which results in the vectors for the positions of the left and right distances, respectively:

\[
\begin{bmatrix} x_l \\ z_l \\ 1 \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} x_r \\ z_r \\ 1 \end{bmatrix}
\]
\quad (19 & 20)

From these position vectors, the length of each distance can be calculated as follows:

\[
L_l = \sqrt{(x_l + \frac{w}{2})^2 + z_l^2},
\]
\quad (21)

\[
L_r = \sqrt{(x_r - \frac{w}{2})^2 + z_r^2},
\]
\quad (22)

and

\[
L_c = \sqrt{x_1^2 + z_1^2}
\]
\quad (23)

where \(x_1\) and \(y_1\) are the results from Equation 15 where \(m = 1\). Following a similar method, linear algebra can be used to predict the ideal lengths of the inner and outer muscles if they were to not interact with the vertebral struts, where \(M_l\) is the left muscle length and \(M_r\) is the right muscle length (see Figure 24, right image):

\[
M_l = \sqrt{(x_1 + \frac{w}{2})^2 + z_1^2};
\]
\quad (24)

\[
M_r = \sqrt{(x_1 - \frac{w}{2})^2 + z_1^2}.
\]
\quad (25)
The two different lengths $M_l$ and $L_r$ can be used to approximate the respective lengths of the contracted and relaxed muscles because these vectors do not substantially interfere with the vertebral column or plates when the robot is bent (see Figure 24). In contrast, the opposing measurements, $M_r$ and $L_t$, pass through the vertebral column and plates, resulting in unrealistic approximations of the muscles during planar bending. Thus, the “ideal” lengths necessary to achieve a maximum bending angle of $\sim 40^\circ$ for the contracted and relaxed muscles can be approximated as $M_l = 80$ mm and $L_r = 130$ mm, respectively, such that the muscle should be contracted by about $\sim 38\%$. In contrast, the muscle lengths for a $\sim 22^\circ$ bending angle are $M_l = 93$ mm and $L_r = 120$ mm, respectively, such that the muscle should be contracted by $\sim 23\%$. The McKibben muscles developed here are capable of $\sim 25\%$ contraction at a maximum pressure of $\sim 520$ kPa; so, to achieve an optimal $25\%$ contraction, the relaxed muscle should be $\sim 122$ mm, which would result in a bending angle of $\sim 25^\circ$. When compared with the actual length of the relaxed muscles (127 mm), the non-actuated muscle at $\sim 40^\circ$ is longer ($\sim 130$ mm), but at $\sim 22^\circ$ it is shorter ($\sim 120$ mm). Also, the linear algebra approximations assume each segment rotates uniformly with the same bending angle; it does not account for the “kick-back” effect observed in the actual robot, which would likely put additional strain on the relaxed muscles. These observations explain why the robot exhibits a bending capacity of about half that of the skeleton without muscles.
Finally, the linear algebra model can be revisited for a three-dimensional investigation (see Figure 25). Although not used for analyses in this research, the 3D motion of an $m$-th segment of the robot can be tracked by its locations, like the 2D model. By analogy, the segment positions are represented as:

\[
\left( \cos \phi_i \quad - \sin \phi_i \quad 0 \quad 0 \right) \cdot \left( \cos \theta_i \quad 0 \quad - \sin \theta_i \quad 0 \right) \cdot \left( 1 \quad 0 \quad 0 \quad 0 \right) = \left( \cos \phi_i \cos \theta_i \quad \cos \phi_i \sin \theta_i \quad \sin \phi_i \cos \theta_i \quad \sin \phi_i \sin \theta_i \right) \cdot \left( 0 \quad 0 \quad 0 \quad 1 \right) \quad (26)
\]

which results in a vector $(x_m, y_m, z_m, 1)$. Then, a segment’s displacement in $\mathbb{R}^3$ space is:

\[
\Delta d_m = \sqrt{x_m^2 + y_m^2 \left( \sum_{i=m}^{n} (L_i - z_m) \right)^2}. \quad (27)
\]
6. CONCLUSIONS AND FUTURE WORK

In this thesis, a 3D-printed, air-actuated robot mimicking the musculoskeletal structure of a seahorse tail was designed, built and tested. McKibben muscles were developed to actuate the 3D-printed skeleton, which obtained a total bending response of \( \sim 22^\circ \) as measured in a two-dimensional plane. Importantly, the robot model does not represent an exact replica of a natural seahorse tail. Instead, it was simplified and used to investigate only the planar bending behavior of the system. The model consisted of only seven segments, whereas natural seahorse tails typically contain 30-40 segments depending on the species (Lourie et al. 2004). Still, the actuator placement in the robot model is representative of the seven-segment span observed in the parallel myoseptal sheets of a seahorse tail (Praet et al. 2012, Neutens et al. 2014). The McKibben muscles implemented into the robot performed on par with theoretical predictions. Thus, the anchoring points of the muscles in the robot and natural tail are comparable, allowing for future research on how the seahorse’s armored, yet highly maneuverable tail operates.

In comparison to the 3D-printed skeleton with no muscles, which achieved a maximum bending angle of \( \sim 40^\circ \), actuation of the robot at \( \sim 520 \) kPa produced a bending response of only \( \sim 22^\circ \). It is suggested that the inextensible, relaxed state of the muscles in the non-actuated quadrants of the structure restrict bending, due to a passive tension developed in the muscles as well as their interference with the vertebral column. The resulting tension and vertebral interference causes the first few segments of the robot to “kick-back” in the opposing direction. As the robot actuates, it attempts to bend into the first quadrant of the reference frame, but the inextensible muscles pull its free end towards
its fixed base. This “kick-back” behavior permits more space for the robot to bend, but at the cost of its total horizontal deflection.

These responses could be addressed in future work. It would be useful to create and test other sizes and orientations of McKibben muscles to remedy such behaviors, and better understand the natural action of a seahorse tail. For instance, shorter muscles that only span two or three segments could be implemented into the model to reduce or eliminate vertebral interference on the convex side of the robot. Such a design could also help prevent excessive tension developed in the non-actuated muscles. Longer, more anatomically accurate robots could also be developed. A robot with 30+ segments would likely exhibit more versatile behaviors and could be tested for its prehensile performance, including how much grasping force it could apply upon actuation.

Additionally, it could be useful to test the robot’s functionality after it has incurred damage. In a previous study, 3D-printed models of a seahorse skeleton were crushed, bent and twisted (Porter et al. 2015); but, the models did not incorporate muscles. Such a robot with McKibben muscles could be utilized in search-and-rescue missions through dangerous terrain, such as collapsed buildings. The ability of the robot to withstand crushing might be more beneficial than current soft robotics as they can be susceptible to tearing or rupture of their air bladders. Alternatively, the medical field could benefit from such a device capable of a high range of motion, but is also resistant to excessive deformations, which could prove useful in robotic surgeries.
REFERENCES


