The design of soft fluid filled actuators driven by conductive nylon

by
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B.A.Sc. (Mechanical Engineering) University of British Columbia, 2014

Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Applied Science

in the
School of Engineering Science
Faculty Applied Sciences

SIMON FRASER UNIVERSITY
Fall 2019

Approval

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Degree:	**Master of Applied Science**
Title:	**The design of soft fluid filled actuators driven by conductive nylon**
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Abstract

Soft robots have become increasingly prevalent due to their distinct advantages over traditional rigid robots such as high deformability and good impact resistance. However, soft robotics are currently limited by bulky, non-portable methods of actuation. In this study, we propose a soft actuator driven by conductive nylon artificial muscles which is able to produce forces up to 1.2N. By utilizing nylon artificial muscles, the system does not require sizable pumps or compressors for actuation. The proposed actuator is made up of two main components, a sealed bladder filled with air and an arrangement of nylon artificial muscles. The quasi static behavior of the actuator is characterized using established hyper elastic models and validated against experimental results (maximum error of 5.3%). Using these models, a set of design considerations are formulated which outline the achievable torques for various actuator dimensions.

Keywords: soft robotics; artificial muscles; nylon; fluidic actuator; polymer

Acknowledgements

I would like to thank Dr. Carlo Menon, my senior supervisor for his support and guidance, Dr. Michael Adachi, Dr. Woo Soo Kim for being my committee. Special thanks to Hadi Moein and Shahram Pourazadi for contributing their time towards aiding me to conduct research experiments. I would also like to thank all members of MENRVA research group for their help and support. Last but not least, I would like to thank my family and my Fiancédf Ali White for providing me with support and encouragement.

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List of Acronyms

SFU	Simon Fraser University
DEA	Dielectric elastomer Actuators
SMA	Shape memory alloy
IPMC	Ionic polymer-metal composite actuator
MENRVA	Mechanisms N Robotics for Viable Applications

Chapter 1. Introduction

1.1. Background

Biology has for some time, been a source of inspiration for engineers designing more adaptable machines. Biological systems rely on body compliance and softness to effortlessly interact with complex environments. These biological systems have inspired designers in the creation of a new class of machines referred to as soft robots. Conventional, rigid robots are used for a variety of applications where they perform exceedingly well when programmed to perform a single task however, often with limited adaptability [1]. In addition, due to their rigid nature, conventional robots are unsafe for interaction with humans [2]. As a result, it is common practice to separate work spaces for humans and robots to prevent collisions and mitigate safety concerns [2]. The limited compliance in conventional robotic systems is large contributor to this problem. Soft robots provide an opportunity to bridge this gap between human and robotic interactions. Due to the compliant nature of soft robotic systems, the body of the robot is able to absorb the majority of the energy in the case of a collision [3]. These robots consist of a continuously deformable structure paired with muscle like actuation technologies that emulate biological systems. As a result, these systems are able capable of deforming with a large number of degrees of freedom when compared to their rigid counterparts [3]. Soft robotics offers an alternative solution to rigid systems, with increased adaptability, agility, and reduced complexity when interacting with their environments.

1.2. Motivation

Soft robots have become increasingly prevalent due to their distinct advantages over traditional rigid robots such as high deformability and good impact resistance. One of the biggest challenges for soft robotics is the design of extendable, portable methods for actuation [1]. The segments of a soft robot are typically actuated in one of two ways: tendons of varying length may be embedded into the soft segments to achieve motion; or pneumatic actuation may be used to pressurize inflatable channels which cause the material to deform to the desired deformation [1]. Tendon systems typically rely on electric motors to contract. Electric motors produce high specific power outputs, but require transmission systems to perform non-repetitive tasks, which increases the size, and weight of the overall system [2]. Pneumatic actuators rely on external pressure sources that are generally limited to pumps, compressors, or cylinders of compressed air [3].

Biological muscles offer many advantages over electric motors and pneumatic actuation methods. Skeletal muscles can produce large forces under varying strains, exhibit fast actuation times, and have high power- to-weight ratios [4]. Researchers in the field of artificial muscles aim to create an actuator that matches these desirable properties. Some of the technologies currently being examined include piezoelectric polymers, shape memory alloys, ferroelectric dielectric elastomers, and polyelectrode gels [2] [5] [6] [7]. These materials deform when a chemical, electrical, or thermal stress is applied [8]. However, these technologies suffer from certain limitations such as low life cycle, hysteresis, high voltage requirements, and low efficiency [2] [9] [10]. A muscle-like technology whose performance could match that of skeletal muscle would be beneficial for the field of soft robotics.

Haines et al. recently discovered a new type of artificial muscles that match or exceed the performance of biological muscles [11]. These artificial muscles are produced by coiling nylon fibres. Nylon fibres are made up of polymer chains oriented in the fibre direction which undergo large reversible contractions when heated. Haines et al. showed that uncoiled nylon fibres can contract up to 4% when a thermal load is applied. They showed that the tensile stroke may be amplified by coiling the fibres to make them chiral. Depending on the coil parameters, the coiled fibres may contract up to 49%, exceeding skeletal muscles (20%) [11]. In addition, nylon actuators have been shown to generate power densities of up to 5.3kW/kg, compared to 0.32kW/kg for the average human skeletal muscle [9].

In this study, soft actuators are proposed which make use of nylon artificial muscles to produce a soft fluidic actuator with no requirement for an external compressor. The artificial muscles are arranged to increase the pressure of the internal fluid while providing a backbone to produce bending motion. The internal fluid provides the proposed actuators with a compliant structure much like pneumatically-driven soft actuators. This study examines the feasibility of using the proposed actuators by investigating the system both analytically and experimentally.

1.3. Objectives

The objectives of this thesis are to:

1. Explore the feasibility of developing a soft bending fluidic actuator which makes use of nylon artificial muscles eliminating the need for an external compressor or pump
2. Utilize established hyper elastic models to investigate the quasi-static behaviour of the proposed fluidic actuator

3. Verify the proposed model

4. Characterize the performance of the proposed fluidic actuator

1.3 Thesis Layout

The thesis has the following layout. Chapter 2 presents an in-depth literature review of the field of soft robotics. A general overview of the field is discussed and its recent emergence into fields where conventional rigid robotics were typically used. Next, a number of soft robotic actuation technologies are explored including pneumatic actuators, smart materials, and cable driven actuators. These technologies have enabled soft robotics to enter into a number of new applications. Some of these applications are explored including soft robotic grippers, medical applications, wearable applications, and soft locomotive robots. Based on these actuation technologies, various soft robotic control systems are reviewed. Lastly, the persistent challenges in soft robotics development are highlighted.

Chapter 3 presents the proposed actuator design and the fabrication of an initial prototype. In this chapter, the actuator operating principles are outlined along with a proposed fabrication method for the sealed fluid bladder and coiled nylon fibres. Finally, an initial prototype is constructed using the proposed methods and presented at the end of this section.

In chapter 4 and analytical model is developed for the proposed actuator design. To enable the robotics research community to utilize the proposed actuator, analytical models were formulated to predict the actuator’s quasi-static behaviour and validated against the experimental results. This provides robotics designers with information on the actuator’s performance prior to manufacturing. The variables in the models were the nylon thermo-electric properties, the actuator dimensions, and the material properties of the silicone bladder. The outputs of the model were the actuator position and the forces generated at the actuator tip.

Chapter 5 validates the analytical models proposed in chapter 4 against experimental results. Six variations of the proposed actuator are fabricated and tested to verify the proposed position and force models. After validating the analytical models, a position controller was developed to demonstrate the simplicity at which the proposed actuator may be controlled. This controller is then used to provide evidence of the potential ability of the soft actuator to be used in robotic applications

Chapter 6 examines the validated analytical models and outlines a set of design considerations for the proposed actuator. The proposed fluidic actuator may be suitable for applications where pressure driven actuators are currently used. However, the size and forces generated by the actuator are limited by the capabilities of the nylon artificial muscles. It is important for the robotics designer to understand how these limitations affect the actuator's capabilities. Using the models developed in chapter 4, a set of theoretical limits is calculated based on the physical dimensions of the actuator to establish the maximum achievable torques and maximum actuator dimensions for a full range of motion.

The vast majority of the thesis is reproduced with permission from the following papers I co-authored:

Sutton, L & Menon C (2019) A soft fluidic actuator based on nylon artificial muscles. Engineering Research Express. Manuscript accepted for publication [15]

Kaur, R, Sutton, L & Menon C (2019) Soft Grippers: A state of the art review. Robotica. Manuscript submitted for publication. [16]

Sutton L, Moein H, Rafiee A, Madden JD, Menon C. Design of an assistive wrist orthosis using conductive nylon actuators. In2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob) 2016 Jun 26 (pp. 1074-1079). IEEE. [16]

Chapter 2. Literature Review

This chapter presents a review on the current state of the art in the field of soft robotics including actuation technologies, soft robotics applications, control systems, and persistent challenges moving forward. on the proposed actuator design and the fabrication process for the initial prototypes. Sections of this chapter are excerpts from the following papers which I co-authored:

Kaur, R, Sutton, L & Menon C (2019) Soft Grippers: A state of the art review. Robotica. Manuscript submitted for publication

Sutton L, Moein H, Rafiee A, Madden JD, Menon C. Design of an assistive wrist orthosis using conductive nylon actuators. In 2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob) 2016 Jun 26 (pp. 1074-1079). IEEE.

2.1. Soft Robotics

Conventional robotic systems are composed of metals, or hard plastics with moduli with moduli in the range of $10^9 - 10^{12}\ Pa$ (Figure 1) [1]. These rigid bodied robots are used in a number of applications where they may be programmed to perform specific tasks efficiently. However, due to their rigid nature, they usually perform these tasks with limited adaptability. In addition, these rigid systems are often unsafe for interactions with humans. To overcome these limitations, engineers have begun to explore using soft materials to build robots. The body of these soft robots are made out of soft materials that can absorb energy and deform in the case of a collision. Due to their flexible structure, these robots exhibit a large number of degrees of freedom. This allows them to exhibit increased levels of adaptivity when compared to rigid bodied robots. Recent developments have shown these robots twisting and bending with high curvatures in a continuous way allowing them to achieve motions that emulate biology [15], employ compliant motion to manipulate objects, move in rough terrain [16], and execute rapid agile maneuvers [17]. Soft robotics is rapidly entering new areas of active development, in the following sections, the underlying actuation technologies, some of the common applications of soft robotics, and the challenges moving forward are explored.

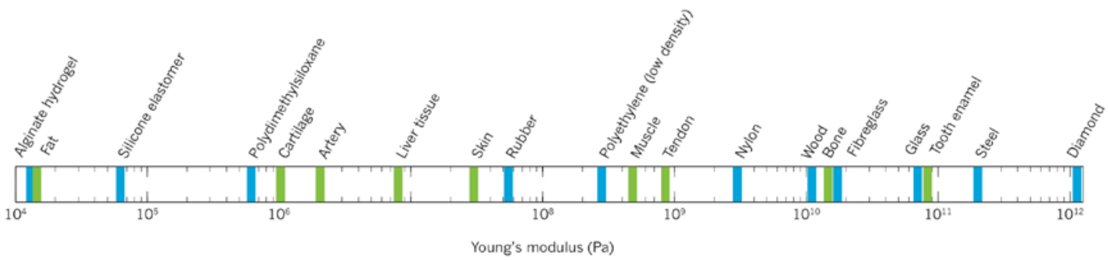


Figure 1 Approximate Young's modulus of selected engineering and materials. Image reproduced with permissions from [1]

2.2. Intrinsically Soft Materials

Recent developments in the design of soft materials has been one of the key enablers for the soft robotics community. Conventional robotic systems typically made use of hard materials such as metals or hard plastics which have a Young's modulus in the range of 10^9–10^{12} Pa [4]. On the contrary, biological systems are often composed of materials such as skin, or muscle tissue, with a Young's modulus in the range of 10^4–10^9 Pa [4]. The soft robotics community has taken inspiration from these biological systems begun to design autonomous systems that are primarily made of up materials with a Young's modulus in the range of soft biological materials.

Historically, advanced elastomers with low Young's modulus, high strains, and toughness were not available from commercial vendors until relatively recently. On the contrary, metals and ceramics have been globally available for use for thousands of years [18]. Although natural rubber was available from the Hevea brasilinesis tree, it was not vulcanized until the 19th century. It also does not provide the required properties for use in soft robotics [3]. In 1948 Dow-Corning was the first to release a commercially available resilient silicone [3]. Eventually, these silicones started to see use as gaskets, sealants and coatings, however it wasn't until recently when these materials started to be used as the machinery itself. These soft materials with a Young's modulus similar to that of biological materials offer many advantages over rigid materials. They offer a considerable reduction in harm that could be caused by a collision with a rigid material [19]. This is beneficial to the robotics community as inadvertent collisions can potentially occur during human robot interaction. In addition, these compliant materials readily adapt to the shapes of various objects making tasks such as grasping significantly less complex. Furthermore, these soft materials can lead to improved mobility for locomotion robots exploring unknown terrain [20].

2.3. Actuation technologies

Soft robotic systems require a flexible actuation system. These actuation systems often take inspiration from biological muscles because of their deformability and adaptability. A number of flexible actuation systems have been proposed. These systems involve force that is transmitted by a fluidic pressure inside the soft structure, through cables embedded in the structure, or by using smart materials such as dielectric elastomers (DEA) or shape memory alloys (SMA).

2.3.1. Pneumatic actuation

Robots powered by pneumatic actuation use a pressurized fluid to deform the soft robotic structure to a desired configuration. These motions may include elongation, contraction, twisting, bending or any complex combination of all these [15]. The desired motions are achieved by structural constraints and through control of the fluid pressure inside the inflatable chambers [16]. The inherently compliant structure of the robot allows it to change its compliance according to the change in pressure of the fluid inside. These characteristics allow pressure controlled soft robots to distribute the pressure uniformly over large areas without elaborate controls and thus allow them to manipulate fragile and irregular shaped objects.

McKibben et al. was one of the first to propose pneumatic muscle actuators to assist patients with paralyzed hands [17]. The proposed muscles are made up an inflatable rubber tube housed in a rigid helically wound braid (Figure 2 a). When the tube is pressurized, the muscle expands radially and contracts axially. These muscles exhibit characteristics similar to that of biological muscles and have been studied extensively [24], [25], [26], [27], [28] [29], [30].

The muscles proposed by McKibben et al. only allow for deformation in the linear direction. To overcome these limitations, researchers have begun to explore channeled actuators to allow for more complex motions. These actuators are composed of an elastomer embedded with a network of internal channels, and a stiff layer bonded to the elastomer. The difference in the young’s modulus of the two materials and the design of the internal network cause the actuator to bend to the desired configuration upon pressurization [31], [32] (Figure 2 b-e). Chang et al. was one of the first to propose a channelled bending fluidic actuator. The actuator used a unique fluidic channel embedded in a soft silicon structure bonded to a thin stiff material [22]. This work was adapted by Ilievski in the creation of a new pneumatic network actuator (PneuNets) [33]. These PneuNets actuators were used in a number of soft robotic designs including: Shepherd’s puncture resistant actuator [34], Stokes’ soft quadruped [35], Tolley’s walking robot [1] Homber's soft gripper [36].

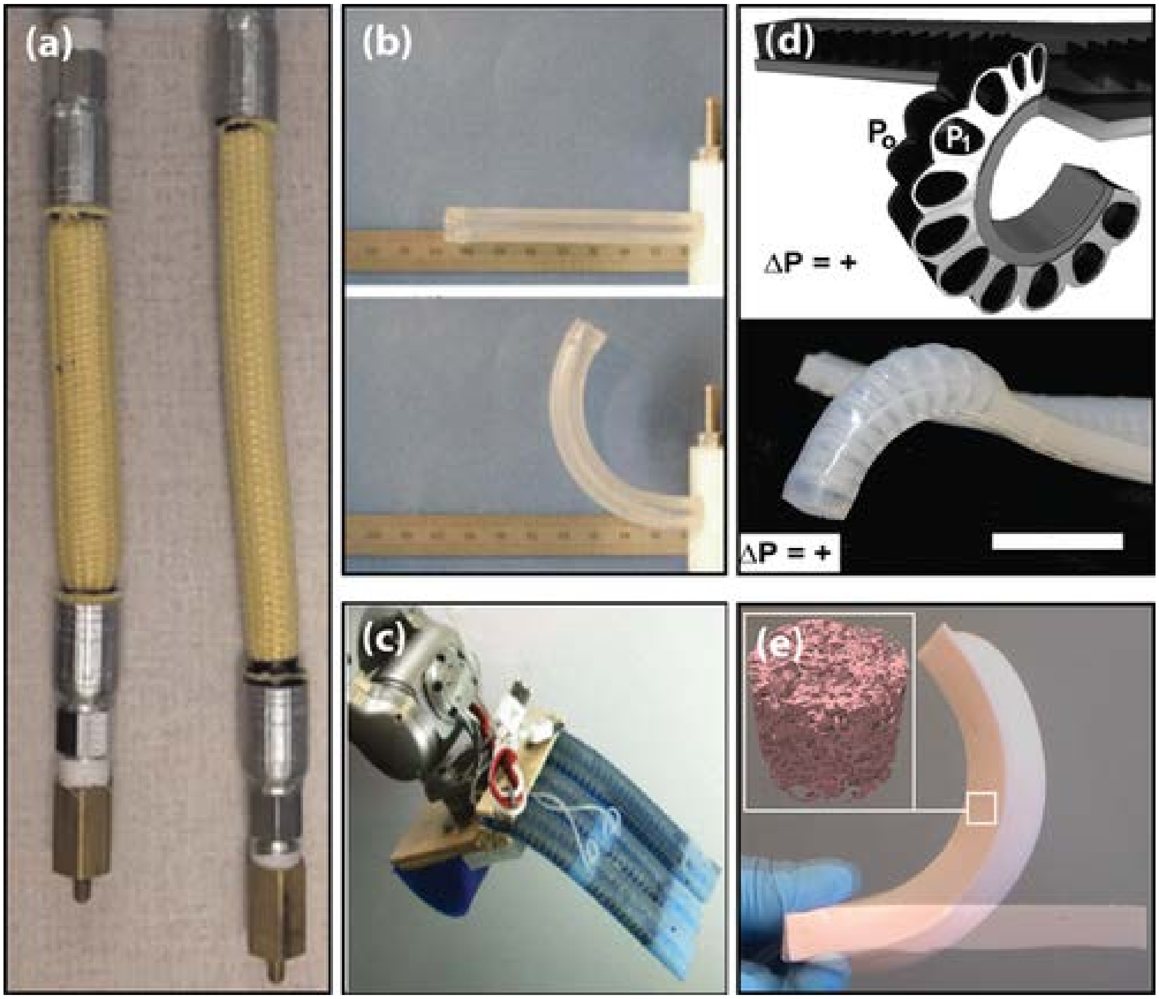
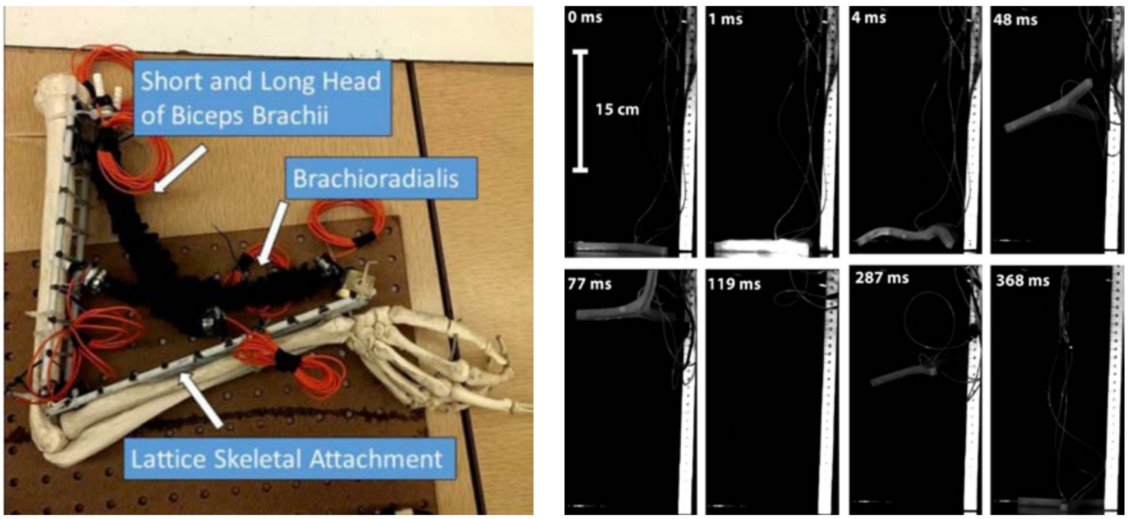


Figure 2 (a) McKibben actuator reproduced with permissions from [37] (b, c) fluid elastomer actuators from [38] (d) pneu-net molded fluid actuator from [39]. (d) Foam based fluidic actuator [40]. Image reproduced with permissions from [3]

Most actuators are controlled by pressurized air as it presents many advantages over the use of other fluids [32]. However, hydraulic actuation is used in cases where higher forces are required [40], [41], [42]. A comparison between pneumatic and hydraulic actuation was conducted by Trivedi [43] in the development of a soft robotic octopus arm. Yamaguchi et al. examined a different type of fluid working fluid in in the design of a robotic hand [44]. The robotic hand used an electro-conjugate fluid that produces a jet flow when subjected to a high DC voltage. The jet flow pressurizing the fingers allows them to bend. Furthermore, the pressure generation by chemical reactions to power the soft bodied robot has also been developed [45], [34], [46] [47].



(a) (b)

Figure 3 (a) Hydraulic artificial muscle attached to a skeletal arm. Image reproduced with permissions from [40](b) Time sequence of a jumping robot powered by chemical explosions. Image reproduced with permissions from [44]

2.3.2. Actuation using smart materials

Advances in the field of materials science has introduced various materials with intelligence embedded at the molecular level. These materials respond to electrical or thermal stimuli by altering their shape [48]. Several of these smart materials including SMAs and EAPS are finding use in soft robotics.

Shape memory alloys (SMAs) have the unique ability to recover from a plastic strain when they are heated above a certain temperature. This property is exploited in the development of SMA muscles which make use of coiled SMA wires that contract when heated. These muscles can be activated using an external heat source or by running an electrical current through the wire (joule heating). Researchers have shown that SMA wires can be used to generate multiple modes of actuation depending on the configuration of the SMA wires. As a result, researchers have found many use cases for SMA wires in soft robotics. Lashi et al. used coiled SMA wires in the development of an octopus like arm robot (Figure 2C). [49]. Kim et al. used SMA wires to design a resilient earth worm like locomotion robot [50]. A dexterous soft robotic hand having 7 degrees of freedom actuated entirely by SMA wires was developed by Kim et al. [51]. Underwater robots inspired by jellyfish and fish actuated by SMAs have also been designed [52], [53].

Electroactive polymers (EAPs) represent another class of smart materials that undergo a change in shape or size in response to an electrical stimulus. EAPs are typically composed of soft materials which mimic the flexibility of biological materials. They can also be configured to undergo large deformations, enabling their use in bioinspired soft robots. DEAs represent an important class of EAPs due to their high energy density and fast response times. [45]. DEAs are constructed by surrounding a soft insulating membrane with two compliant electrodes. When a voltage is applied to the electrodes, the insulting membrane contracts in the direction of the electric field and expands in the transverse direction. Researchers have studied the characteristics of various configurations of DEA's [46], [47], [48], [49]. Examples of soft robots that are actuated by DEAs include Kofod's tulip-shaped soft gripper [50], Araromi's rollable gripper for space applications [51], Shinktake's gripper that uses both electro adhesion and electrostatic forces (Figure 2D) [52] and Lau's soft gripper [53].

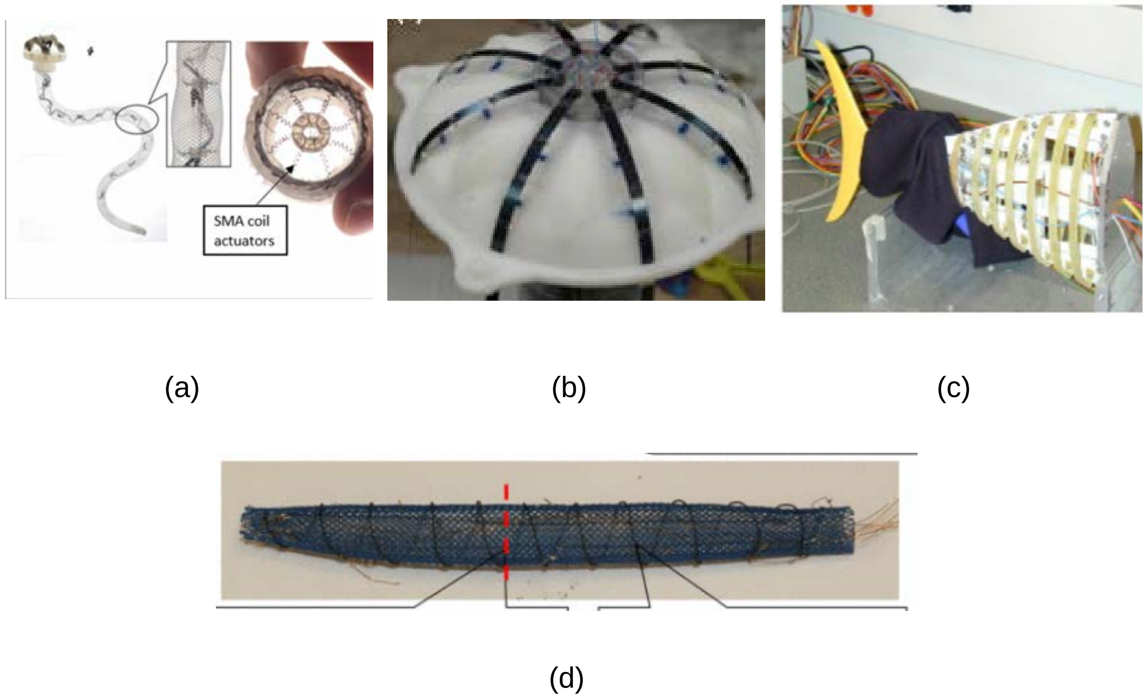
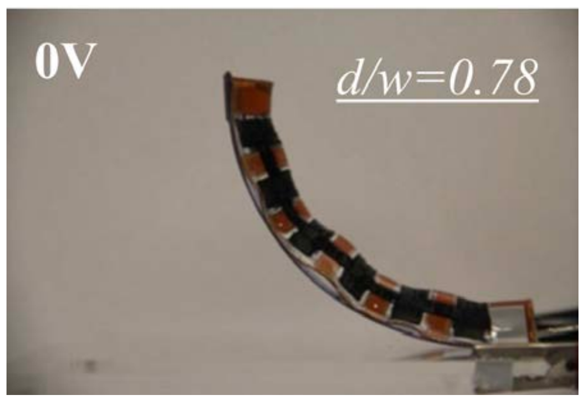


Figure 4 (a) Soft robotic octopus arm powered by SMA coil actuators. Image reproduced with permissions from [16]. Jellyfish soft robot powered by SMA actuators [52]. (c) A self contained soft fish robot powered by SMA actuators. Image reproduced with permissions from [53]. (d) A resilient earth worm robot coiled with SMA actuators to produce locomotion. Image reproduced with permissions from [50].

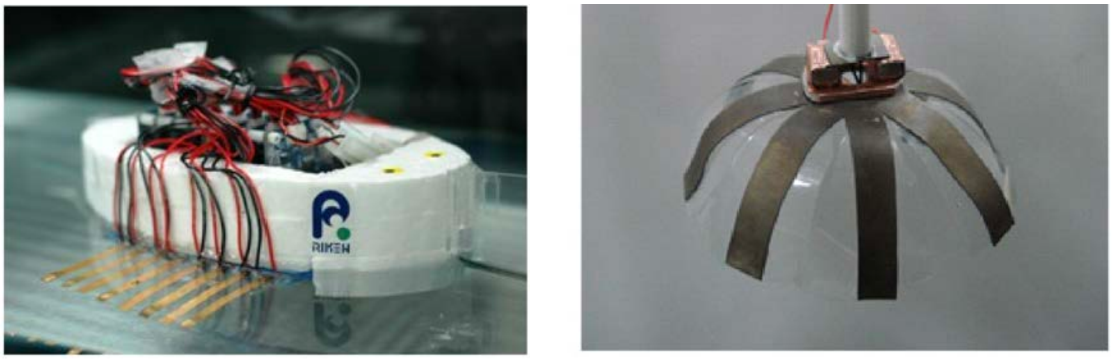
Ionic polymer-metal composites (IPMC) represent another class of EAPs which have been studied for soft actuation. IPMCs consist of a thin ionic conductor membrane surround by metal electrodes. When a voltage is applied to the metal electrodes, the counter-ions diffuse towards the compliant electrode. The charge and displacement of the ions cause the actuator to bend. These actuators require lower voltages when compared to DEAs. Due to the ionic nature of the conductor, these actuators operate best in humid environments. As a result, researchers have found use cases for IPMCs in the design of underwater soft robots [63], [64], [65]. However, researchers have also successfully used IPMCs in dry applications by encapsulating the actuators [66].

(a)



(b) (c)

Figure 5 (a) A rollable soft gripper powered by DEA actuators. Image reproduced with permissions from [51]. An electro adhesion gripper actuated with DEA's. Image reproduced with permission from [52]. A soft bendable actuator used in the development of a DEA powered soft gripper. Image reproduced with permissions from [53].



(a) (b)

Figure 6 (a) A planar swimming robot powered by ionic polymer artificial muscles. Image reproduced with permissions from [63] (b) A soft jellyfish inspired robot actuated with ionic polymer metal composite muscles. Image reproduced with permissions from [65].

2.3.3. Cable driven actuation

Cable driven actuation methods use cables along the body of the soft robot connected to traditional motors to deform the robot to the desired configuration. This allows the designer to displace the source of actuation while still providing the required forces at the robot’s end effectors [58]. By utilizing cables and soft materials robots can be created that conform to their environment and are safe for interactions with humans. In addition, cable driven robots, involve low inertia, low volume requirements, and a fast response time [58]. Cable driven actuators have been used to create a number of soft robots including: a prosthetic hand by Carozza et al [59], a soft hand gripper by Manti et al. [60], [61], a minimally invasive surgical gripper by Rateni et al. [62], a crawling, grasping robot by Calisti [63] and an octopus inspired robotic arm by Giannaccini [64]. Cable driven actuation methods have also found use in wearable robotics to assist people with disabilities [65], [66]. A number of continuum robots have also been proposed which make use of cable driven actuation mechanisms [67], [68], [69], [70], [71].

(a)

(b)

(c)

(d)

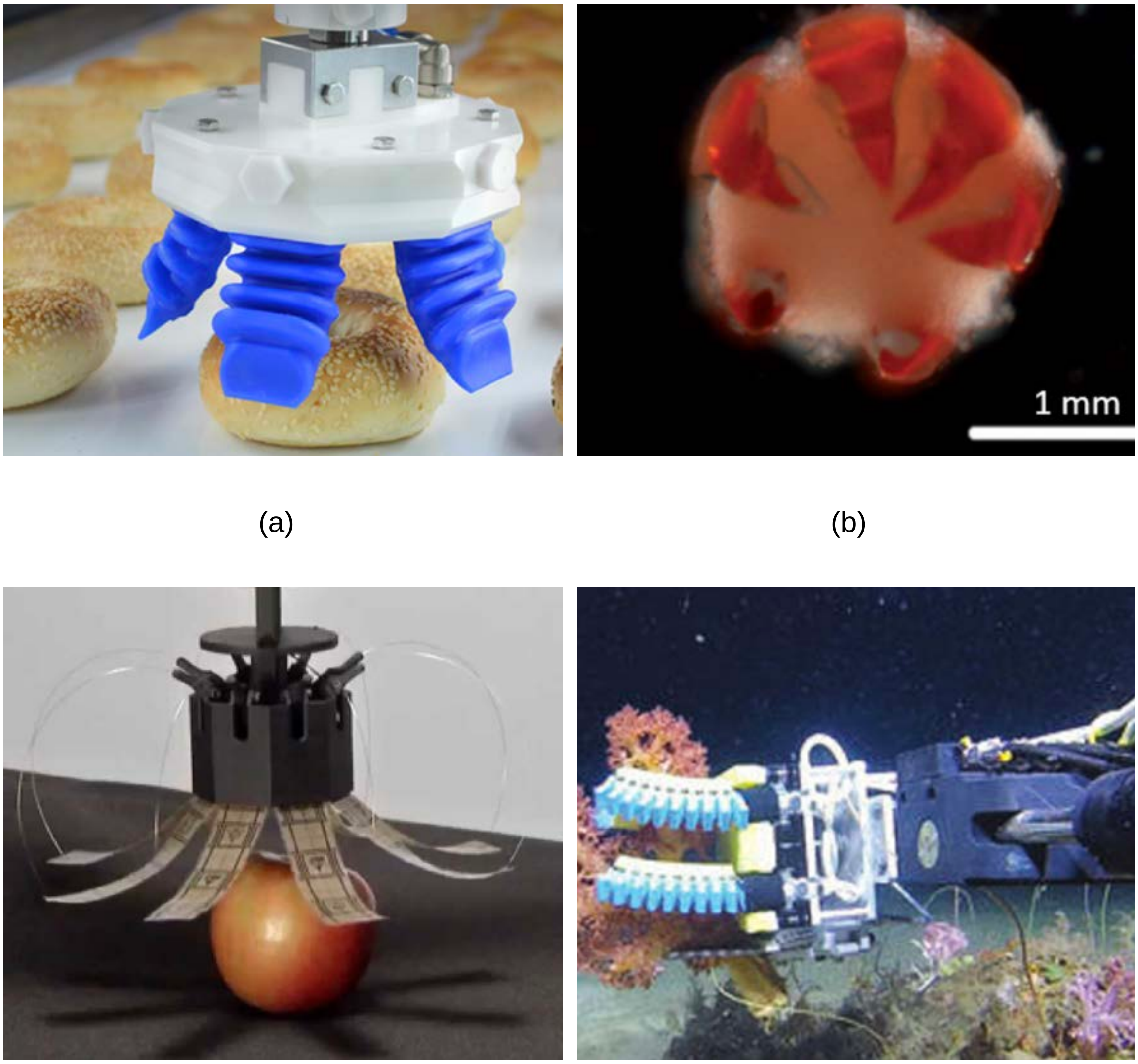
Figure 7. (a) A cosmetic prosthetic hand driven with cable actuators arranged along the joint path. Image reproduced with permissions from [68]. A soft robotic manipulator activated by cable driven actuators. Image reproduced with permissions from [62]. (c) A bioinspired continuous manipulator which utilizes pressure and tendon driven actuation. Image reproduced with permissions from [70]. (d) A soft wearable robot for hand assistance. The robot uses a tendon driven actuation system aligned with the hand joints to assist with flexion and extension. Image reproduced with permissions from[66]

2.4. Soft Robotics Applications

Soft robotics is a rapidly growing field and researchers are consistently finding innovative applications for soft robots. Due to their flexible nature and increased adaptability, researchers are able to use soft robots in human friendly environments where rigid robots have failed.

2.4.1. Grippers and Manipulators

The compliant nature of soft robotic graspers makes them an appealing choice for use in grasping applications. In particular, recent developments in the field of soft robotics has allowed robots to enter the food industry. The uncertainty in size, weight, and compliance of food items makes interaction with a robotic device a challenging task [81], [82]. Soft robots are able to overcome some of the limitations of rigid robotics by providing the ability to conform to the shape of the object being interacted with. Researchers have proposed a number of soft manipulators to pick and place food items [83], [84] or harvest fruits and vegetables [85], [86], [87], [88]. Not only are these grippers used in an academic setting, but a number of products are actively being developed in the market [89]. Soft Robotics (Figure 3A) is one such company that produces soft grippers for handing food items [90]. Festo and Grabit [91] are other examples of manufacturers that are fabricating soft grippers for use in the food industry.



(a) (b)

(c) (d)

Figure 8. Some applications of the soft manipulators. (a) Soft Robotics' gripper handling food item (reproduced with permission from [90]). (b) Theragripper grasping a group of cells [92]. (c) Grabit electroadhesion soft gripper. (d) Soft gripper being used for underwater application [42]. Images reproduced with permissions from [90] [91] [41] [42]

2.4.2. Medical Applications

Soft robotics has been adopted for wide use in medical applications. The compliant body of soft robotics allows for safe interaction with human tissue and has facilitated the introduction of soft medical robots [93].

Heart disease is currently the second leading cause of death in Canada with roughly one in twelve Canadians living with heart disease above the age of 20 [94]. There are currently several methods for treating heart failure including medication, reparative surgery or through the use of an implanted cardiac device [3]. Implanting cardiac devices such as pacemakers, heart valves, or pumps may be used for a number of reasons. An implantable pump may serve as a temporary assistive device while the damaged heart heals naturally, it may be used to sustain heart function while the patient is awaiting a transplant, or to permanently assist the heart function for the duration of the patients life [95]. Cardiac Pumps are available in various forms based on the intended function and lifetime requirements, however, they can be generally described as (i) blood contacting vs non-blood contacting, and (ii) pulsatile versus continuous [3]. Although a number of techniques have been explored to provide a pulse like output for continuous pumps, a pulsatile system that matches the cyclic pumping of the heart has yet to be achieved [3]. Currently there is only one FDA approved total artificial heart which replaces both ventricles of the heart, pumping blood to both the body and the lungs (SyncCardia) [96]. As of 2010 the system had been implanted in over 500 patients, however the cost is too prohibitive to meet the needs of the majority of patients [96]. As a result, researchers have begun to explore the possibility of using soft robotics to reduce the size, and cost of cardiac pumps.

The Walsh lab recently proposed a soft robotic device to match the intricate motion of the heart [95]. To match the motion of the heart, the device was designed to twist during contraction. The proposed device is shown below in Figure 9. The device consists of seven Mckibben actuators arranged in a helical orientation to provide twisting at its apex while contracting the heart in the circumferential direction. The resulting device was able to pump 92 mL per cycle which is well above the typical stroke volumes of a heart (~70 mL)

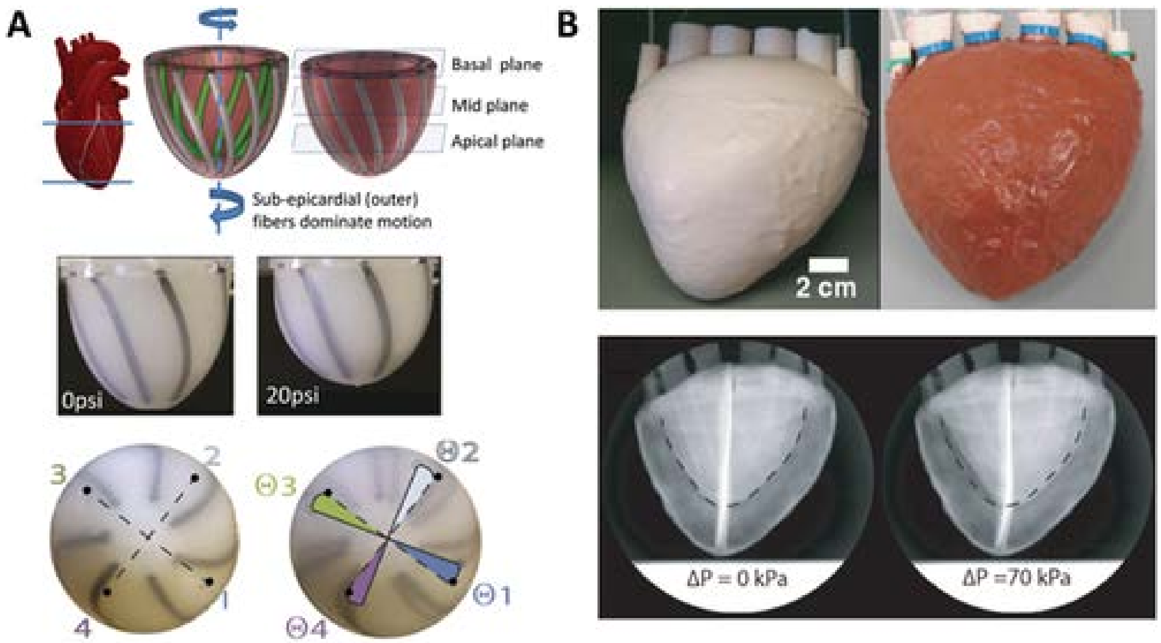


Figure 9 Soft robotic actuators arranged to mimic heart pumping motion. (a) Soft pneumatic actuators arranged helically to simulate the pumping and twisting motion of the heart [95]. (b) Heart fluid pump produced using foam based soft fluidic actuators. Soft Robotic-Based Heart Actuators. [40]. Image reproduced with permissions from [3]

In addition to cardiac devices, soft robotics has found use as an embedded drug delivery system for the human body. Researchers at the University of California have developed a soft robot that can be implanted inside of the body. This robot is actuated with laser light and can be used to deliver drugs to parts of the body or for acquiring tissue samples [86]. A similar gripper was proposed by researchers at John Hopkins university. The proposed gripper can be used for drug delivery and dissolves inside the body after delivering the required payload [87], [88].

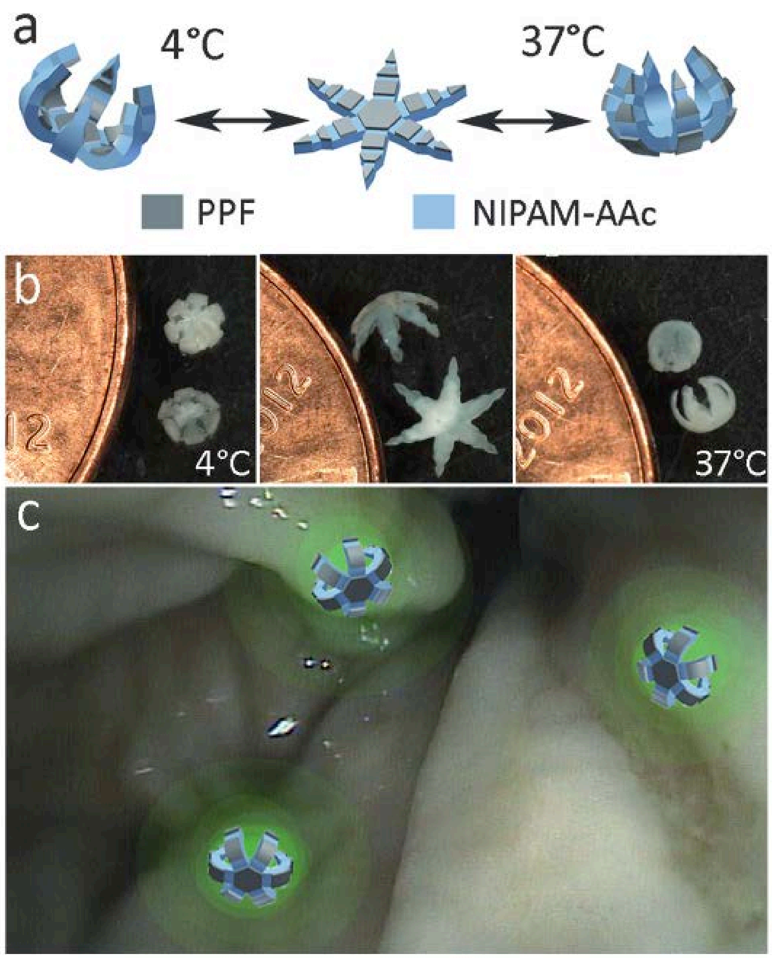


Figure 10 Design of theragripper drub delivery system (a) schematic of the theragripper device. (b) Open and closed theragrippers. (c) Conceptual illuastration of theragrippers inside the body. Image reproduced with permissions from [87]

2.4.3. Wearable applications

The human limbs play in important role in activities of daily living. Unfortunately, when injury or disease affects the functionality of these limits, there are a number of consequences which disrupt the quality of life for those affected. Stroke cerebral palsy, muscular dystrophy, spinal cord injury, traumatic brain injury, are only some of the many things that may affect one's ability to accurately control their extremities.

Impairments to the hands and wrist severely affect the patient's ability to perform activities daily living (ADL) [100]. Conventional means of rehabilitation involves a physio therapist manually manipulating the patient's wrist through its range of motion [101]. Positive outcomes of physical rehabilitation are heavily dependent on the onset, duration, intensity, and frequency of the training [101]. These intense repetitions of the affected limbs can create a significant burden for the health professional administering the training [102]. Furthermore, outside of scheduled clinical hours, there are few tools which allow the patient to continue with his physical therapy in their own home. This deficit highlights a large amount of unaccounted time that could be semi-structured to be complementary to a stroke therapy regime. In response to these problems, prevailing research has presented a number of solutions in the form of robotic aided physical therapy [101]. Robotic rehabilitation devices can assist in the rehabilitation process by performing the repetitive movements needed to restore functionality for stroke patients suffering from hemiparesis or hemiplegia. Studies have shown that robotic aided therapy can produce results comparable with conventional means of physical therapy [103]. Furthermore, robotic therapeutic devices could be administered by physio therapists for the patient to use in the comfort of their own home, decreasing hospitalization costs and increasing the frequency of therapy for the user.

A number of wearable assistive devices have been proposed for rehabilitation purposes that consist of rigid actuation systems. These devices can be used in a clinical setting but are not well suited for assistive tasks or for use in the patient's home [104]. Recently, researchers have begun to explore soft robotic technology in the design of rehabilitative devices. These devices utilise compliant materials such as soft actuation systems for supporting the complex motion produced by the upper extremities. These soft robotic systems can be manufactured using low cost techniques, provide increased adaptability with their operating environment and are therefore well suited for wearable applications.

Researchers have suggested a variety of soft robotic systems for rehabilitation and assistance of the hands, wrist, and elbow. A number of soft glove devices have been proposed which provide assistance in repetitive flexion and extension of the fingers. These gloves may also be used to assist with the grasping of objects if the individual suffers from functional grasp pathologies [75]. In addition to hand motion, some researchers have chosen to focus on developing assistive devices for the wrist, elbow and shoulder. Barlett et al. proposed a soft wrist device actuated by McKibben type muscles to support all degrees of freedom of the wrist (Figure 11) [105]. Unlike conventional assistive devices, this robotic system could be used outside of a clinic environment. Sasaki et al proposed a similar device to actively support the wrist [106]. The device was actuated by pneumatic soft actuators and was capable of flexion and extension.

In addition to upper extremities, researchers have also proposed soft wearable robotic systems for the lower extremities. Wehner et al. was one such research group who proposed a soft lower body exosuit [107]. The system was equipped with custom McKibben style pneumatic actuators that could assist the hip, knee, and ankle. The system was ultra-lightweight when compared to its conventional rigid alternative and provided a lower mechanical impedance (Figure 11). The system was able to transfer forces of up to 400N to certain locations on the body which are suitable to handle this sort of load. Park et al. proposed a soft wearable device for active knee motions. The system was composed of a number of pneumatic artificial muscles to and elastomers to assist the knee with extension and flexion. Finally, a wearable soft robotic system was designed for the ankle which was again proposed by Park et al [108]. The device took inspiration for the human musculoskeletal system and was powered by pneumatic artificial muscles. The robotic system was able to provide assistance in flexion and extension of the angle without restricting the additional degrees of freedom of the ankle joint.

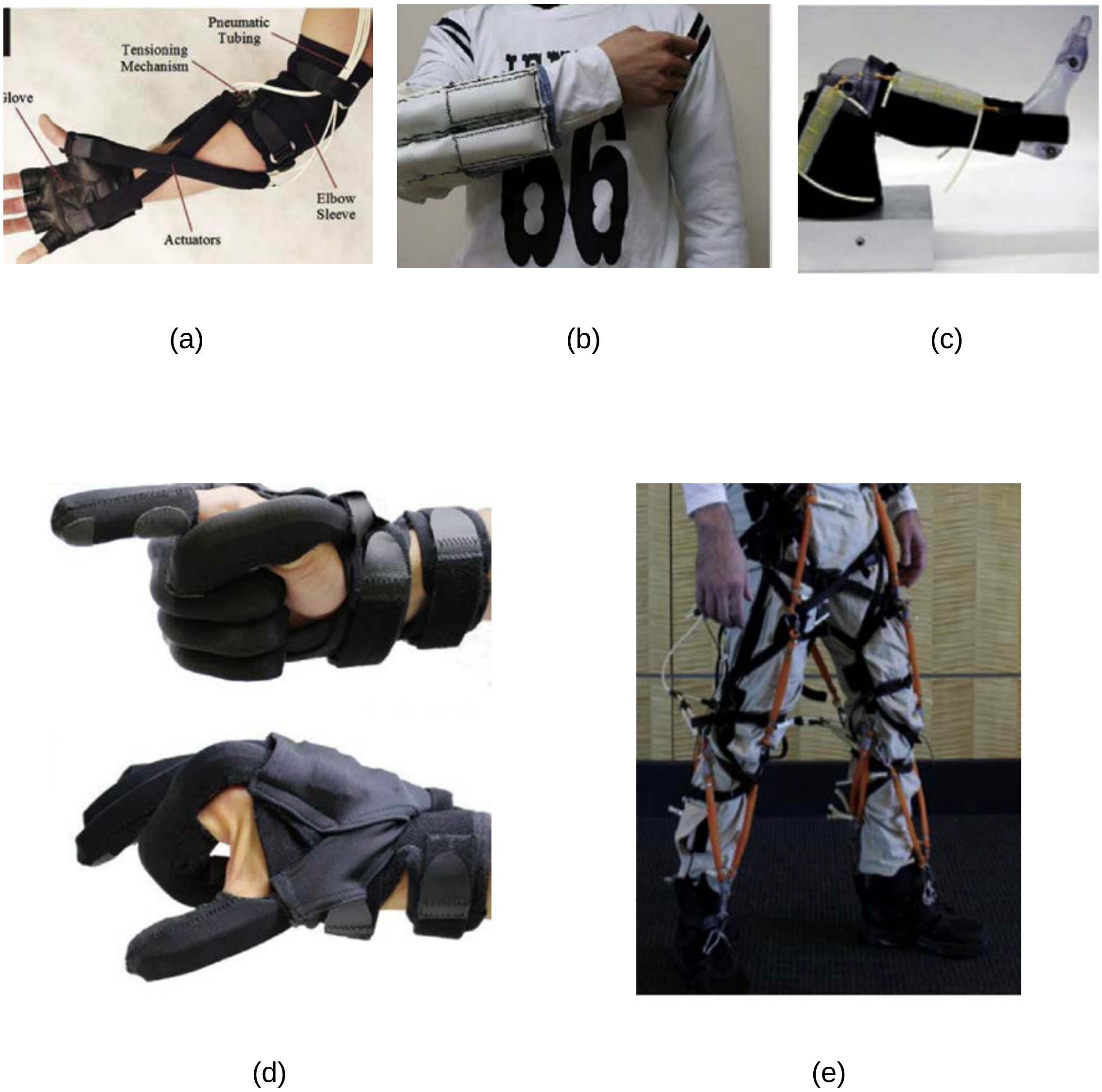
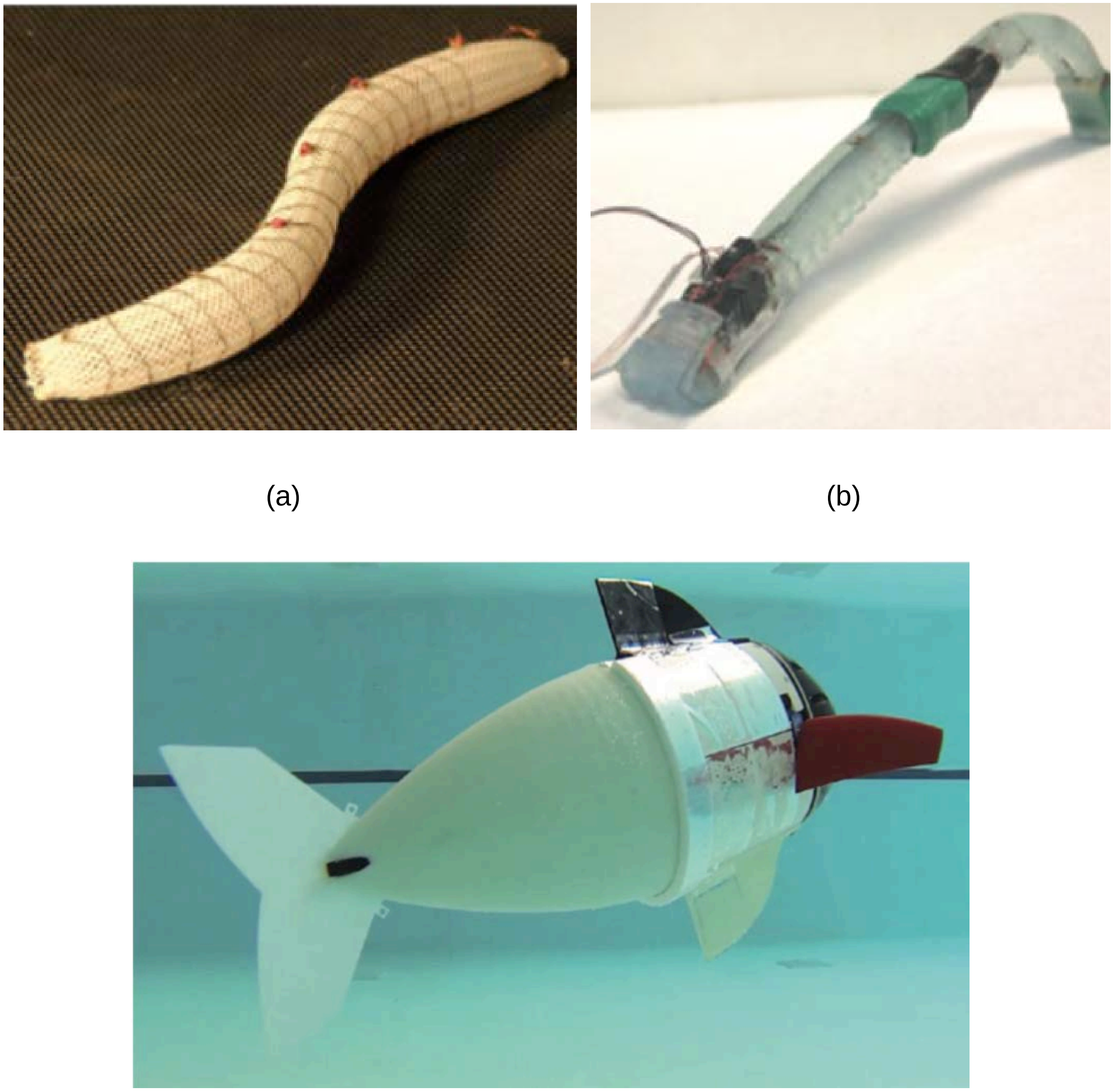


Figure 11 Wearable or assistive soft robotic devices. (a) Wearable soft robotic device for the wrist [105]. (b) Soft pneumatic wearable elbow assistive device. [106] (c) Wearable assistive device for the foot and ankle [108]. (d) Wearable assistive device for the hand [75]. (d) Lightweight soft exoskeleton for lower body gait assistance. [107]. Images reproduced with permissions from [105], [106], [75], [107], and [108] respectively.

2.4.4. Locomotion

Recent work has explored the modes of locomotion enabled by soft bodied robots. Notably, Calisti et al. developed a soft lightweight structure with locomotive and grasping capabilities [63]. Another soft robot that has both walking and manipulative capabilities was designed by Stokes et al. [29]. This robot has the particular capability of grasping and retrieving an object using the capabilities of a soft quadruped and rapid locomotion by using a wheeled hard robot. Studies of caterpillars have also led to soft robotic systems. Lin et al. proposed a resilient earth worm like soft robot which was actuated by SMA's and was able to adapt to a variety of environments [109]. Similarly, Katzschmann et al. designed a self-contained autonomous robotic fish [110]. The fish was actuated by soft pneumatic actuators and was able to swim forward, turn, and adjust its depth. The robot was able to execute manoeuvres at speeds similar to its biological counterpart. Soft robots are also being used outside of academic settings, Pneubotics has developed a soft robot to inspect corrosion in enclosed areas such as in pipes [89], [90]. The potential features and the continuing developments in soft robots may make their use popular in everyday life.



(a) (b)

(c)

Figure 12 (a) A resilient earth worm robot coiled with SMA actuators to produce locomotion. Image reproduced with permissions from [51]. (b) caterpillar inspired locomotive robot. Fabricated from silicone and tethered to its power source. Image reproduced with permissions from [109] (c) A soft robotic fish which was able to swim and manouvre. Image reproduced with permissions from [110].

2.5. Control Systems

Position and motion control of soft robotic systems remains a challenging problem due to several factors. Soft actuators are typically composed of materials that cannot be modelled with linear dynamics [4]. These materials exhibit viscoelastic properties which can lead to hysteresis and inaccurate open loop controllers [3]. The actuation systems also play a role in designing a controller for a soft robotic system. Pneumatic actuators often exhibit slow response times after a pressure stimulus. This is often a result of the high impedance of the tubing and valve orifices connected with the fluidic actuator [3]. Furthermore, pneumatic actuators may be controlled with miniature binary solenoid valves which can only switch between two states, fully on and fully off. This makes analog control systems infeasible for these pneumatic actuator configurations [3].

For soft robotic actuators, the control problem consists of finding the correct combination of inputs to reach the desired shape, position, and velocity. In an open loop control system, the required inputs are determined without observing the current state of the actuator. The inputs may be determined using a mathematical model or though experimentation. For example, Duriez et al. used finite element modelling to simulate the motion of a soft fluidic actuator [113]. This model was then implemented along with an open loop controller to control the fluid input to the actuator. Similarly, Marchese et al. used a piecewise curvature function to model a soft robot with multiple links [114]. The proposed control system would search for the required sequence of inputs that would achieve the desired motion. Hines et al. proposed a graphical and numerical optimization technique to model volume changes in a soft fluidic actuator surrounded by dielectric elastomer actuators [115]. The actuator was made of a hyperelastic material, as a result, the dynamics of the motion could not be captured by the proposed models.

Instead, the model was used to predict the actuator motion after it had reached steady state.

Open loop control systems have several drawbacks. Firstly, there is no feedback system to indicate if the actuator ever reaches the desired state. For instance, if errors occur during manufacturing or the system is operating in a new environment with external disturbances, an open loop controller may fail [3]. Second, steady state analysis may not be sufficient for the given task [116]. The steady state does not predict any intermediate dynamic motion of the system response. This dynamic motion may negatively impact the robot's ability to complete the desired task. Third, relying on a model to predict system state works only as well as the accuracy of the model [3]. For example, the model proposed by Farrow et al. performed well within certain pressure ranges. As a result, the controller could only be used within these pressure ranges, ultimately limiting the full range of the actuator [117].

The challenges with open loop control systems can potentially be mitigated by adding some form of feedback using internal or external sensors. A number of researchers have taken this approach in designing a controller for their proposed soft robotic system. Farrow et al. in [117] designed a soft robotic actuator with Galinstan based curvature sensors embedded into the actuator. Similarly, Bilodeau et al. proposed a soft robotic hand with EGaIn channels arranged along the fingers [119]. These channels provided feedback when objects were grasped or manipulated. Case et al. chose to use elastomer strain sensors embedded in soft bendable beams to provide analog feedback on the bending angle of the beams [120]. The proposed control system used a "bang-bang controller" for the pressure input to the system.

For more complex dynamic systems, designing a controller quickly becomes more difficult. Firstly, systems with non-negligible times to overcome system inertia may take time to increase or decrease the stimuli to the actuator motion [3]. For example, for a pneumatic system, it may take time for the compressor to increase the pressure in the system due to the compressor start time or fluid resistance in the values and connecting hoses. Secondly, soft robotic devices with integrated sensors may have their own dynamic systems which exhibit time delays, or hysteresis [121].

Polygerinos et al. argues that for “fast and accurate control of such systems, accurate models are needed potentially requiring a combination of both feedforward and feedback control” [3]. Turkseven et al. presented a robotic system which used such an approach [122]. The robotic system used a feedforward model-based controller for a pneumatic system which accounted for the delay in the pressure response caused by long transmission lines. The model could be modified to use feedback from controllers which monitored a number of discrete states of the system. In [123] Zhoa et al. proposed a soft orthosis which used a state machine controller to generate controlled curvature motion. Similarly, Skorina et al. proposed a soft robotic manipulator which used an iterative slide mode controller [124]. The feedback system in the controller provided correction to the control input at each time step. Furthermore, a feedforward model was included to predict the manipulator position at steady state given the pressure input to the system. By adding the feedforward model, the system was able to demonstrate improved control and performance while experiencing payload disturbances.

2.6. Challenges

Many of the exciting applications for soft robotics including portable orthosis, and locomotion robots, require an autonomous mobile system. However, most experimental soft robotic systems rely on power and control signals delivered through pneumatic and electrical tethers. Conventional pressure sources are generally limited to compressors, pumps, and compressed air cylinders [91]. These compressors may use valuable electrical energy, and cylinders of compressed gas have limited use time. What has been missing for fluidic systems is completely self-contained soft system capable of generating complex movements [15]. Such a system may make use of portable energy sources which might also be compliant and soft in nature. These self-contained systems will also need to make use of lightweight, compact actuation systems to reduce the overall bulk added to the system.

In addition to designing self-contained devices, robust control systems remain a challenging problem for the soft robotics community. Polygerinos et al in [3] state that while empirical approaches have highlighted the exciting potential for soft robotics, the lack of robust models and control systems for soft actuation systems greatly limit their potential. They highlight that, soft actuation systems have been the focus of many researchers in recent years, however, the modelling and characterization of such systems has been limited [3]. In order for these soft robotic devices to enter into exciting applications involving robot human interaction, these devices will require a number of new design concepts and systematic understanding of the relationship between actuator inputs, control and performance [121]. Furthermore, very few of the technologies described above can be evaluated independently (actuators, control, materials, fabrication). The designer will typically have to look at each system independently, evaluating design trade-offs for various combinations of actuation systems, materials, and sensors. For example, one actuator may be difficult to manufacture but offer increased softness and compliance. Other systems may produce small forces but offer complex bending configurations. All these factors will also play a role in the modelling and control of the system. As these technologies mature, the soft robotics community has begun to highlight some of the complex problems involved with integrating such systems.

Chapter 3. Actuator Design and Early Stage Prototype

This chapter elaborates on the proposed actuator design and the fabrication process for the initial prototypes. The presented materials are toward fulfillment of the 1st objective of the thesis; Propose and develop a soft bending fluidic actuator which makes use of nylon artificial muscles eliminating the need for an external compressor or pump. The entirety of the chapter is an excerpt from sections 1-3 of the article published in *L. Sutton and C. Menon "Design of a soft fluidic actuator using nylon artificial muscles," Engineering Research Express Accepted June 2019.*

3.1. Actuator Concept

The proposed actuator is made up of two main components, a sealed bladder filled with a compressible or incompressible fluid and an arrangement of nylon artificial muscles. The sealed bladder is made up of a soft deformable material and ideally takes a semi-cylindrical shape to maximize bending [126]. The flat component of the sealed bladder is then embedded with nylon artificial muscles. Furthermore, nylon artificial muscles are wrapped radially around the bladder as shown in Figure 13. Similar to conventional bending fluidic actuators, the actuation path is dictated by the shape of the actuator and the relative difference in the Young's modulus of the two materials [127]. Bending is achieved when the artificial muscles activate. When activated, the artificial muscles contract which cause the fluid pressure in the sealed bladder to increase. This increased pressure creates a force which acts to expand the actuator axially. The axially arranged artificial muscles prevent axial extension and instead impose a bending motion in the actuator.

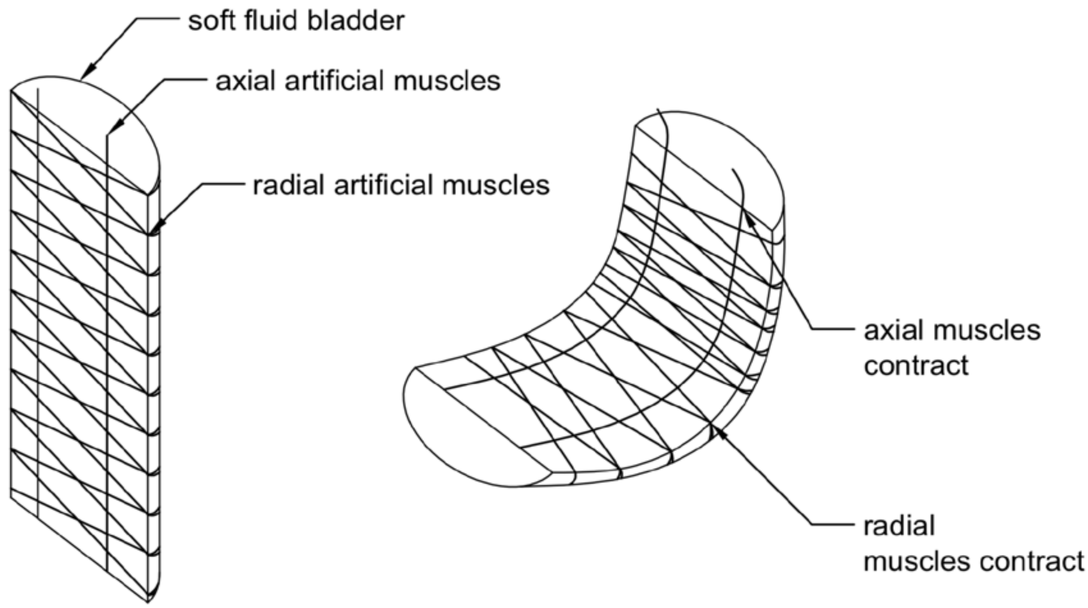


Figure 13 Depiction of actuator operation. Reproduced from [15]

3.2. Actuator Prototype

A prototype was fabricated to demonstrate the feasibility and performance of the proposed actuator design. The nylon artificial muscles were created from silver coated Nylon 6, 6 sewing thread. The conductive silver coating allowed for joule heating to be used for activation [131]. The fibres were coiled using a dc motor while a 200g weight hung from the end of the fibre. The coils were then stretched by 30% and placed into an oven at 200°C for 60 minutes [17]. This heat treatment is used to anneal the fibres, relieving stresses induced by the coiling process [17].

The silicone structure was created using Silicone TC-5005 (BJB Enterprises, Inc.), because it provides a soft compliant surface in addition to high elongation, and high tear resistance [132]. The actuator was prepared using two negative molds created from ABS plastic using a Stratysis 3D printer as seen in Figure 14. A liquid silicone prepolymer was then poured into the molds to produce the final structure. After pouring the prepared silicone in the mold, it was left to cure at room temperature for 18 hours. The silicone was removed from the molds without any visible residue.

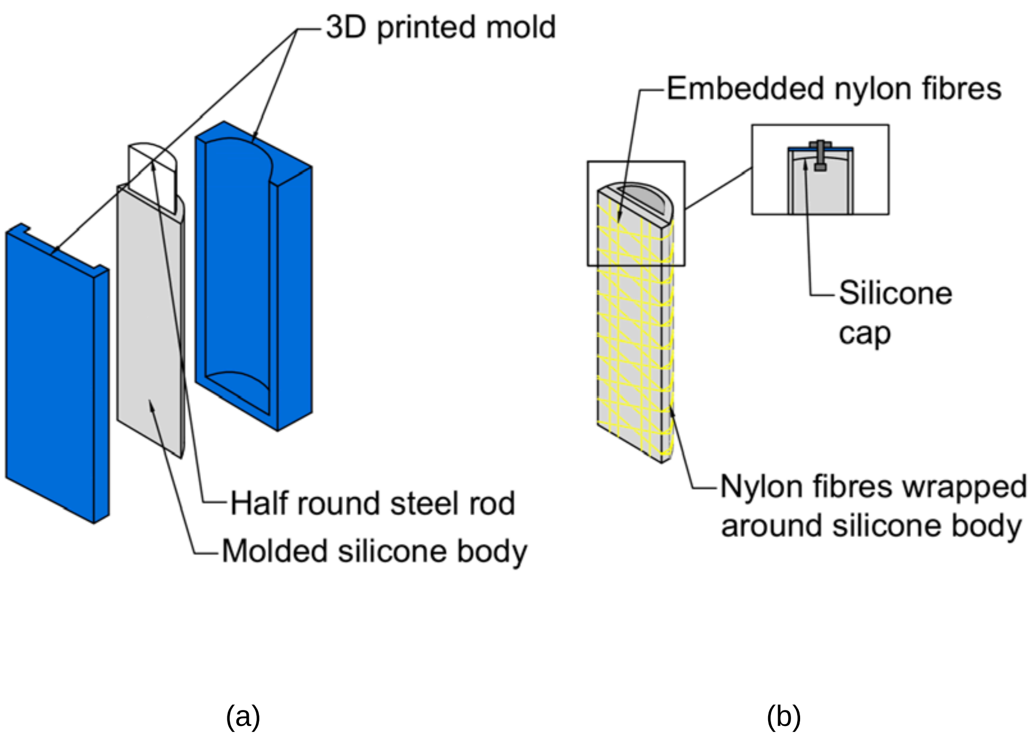


Figure 14. Depiction of the soft actuator fabrication process. (a) Molding the actuator body using a 3-D printed part. (b) The nylon strain limiting layer is attached to the flat face of the actuator. Nylon is wound along the entire length of the actuator. The steel rod is removed from the silicone body and the ends are closed off with silicone. One end is sealed with a vented screw connected to a pressure sensor to measure the internal air pressure in the actuator. Reproduced from [15]

After removing the silicone from the molds, the structure was wrapped radially by hand with nylon artificial muscles. The actuator was equipped with pressure and temperature sensor and sealed with a gasket mount (Figure 15).

(a) (b) (c)

Figure 15. Fabricated actuator. (a) Top view of the silicone actuator after being removed from the mold (b) Bottom view of silicone actuator showing the axially arranged nylon artificial muscles. (c) Silicone actuator wrapped in nylon artificial muscles (top view). Reproduced from [15]

Chapter 4. Analytical Modelling

This chapter develops analytical models for the proposed actuator design. The presented materials are toward fulfillment of the second objective of the thesis; Utilize established hyper elastic models to investigate the quasi-static behaviour of the proposed fluidic actuator. The entirety of the chapter is an excerpt from section 3 of the article published in *L. Sutton and C. Menon “Design of a soft fluidic actuator using nylon artificial muscles,” Engineering Research Express Accepted June 2019* [15].

To enable the robotics research community to utilize the proposed actuator, analytical models were formulated to predict the actuator’s quasi-static behavior and validated against the experimental results. This provides robotics designers with information on the actuator’s performance prior to manufacturing. The variables in the models were the nylon thermo-electric properties, the actuator dimensions, and the material properties of the silicone bladder.

4.1. Nylon Thermo-Electric Model

When the nylon actuators contract, the actuator radius is decreased while the length of the actuator is constrained by the axially arranged nylon. As a result, the internal volume of the actuator decreases and the internal fluid pressure in the actuator increases. The increased internal pressure causes the actuator to bend to the desired configuration. Using the nylon thermo-electric model and the silicone material model, an analytical model was created to relate the nylon contraction to the internal fluid pressure.

The thermo-mechanical model for silver coated nylon actuators was characterized in previous research [17]. The forces generated by the nylon muscles can be modelled as [133]:

$$F = k(x - x_0) + b\dot{x} + c(T - T_0) \qquad (1)$$

where F is the force generated by the nylon, x is the displacement at the end of the fiber, T is the temperature, and k, c, and b are constants determined from calibration. The tensile stroke is defined as the amount of contraction exhibited by the muscles when activated. Kinzaid et al. showed that the tensile stroke is a function of the wire temperature and is independent of the load applied if the stress in the wire remains below the tensile strength [133]. Sharafi et al. showed that the tensile actuation is a function of the temperature of the wire and the coil geometry [134]. This relationship can be modelled as [134]:

$$\varepsilon = \alpha - \gamma T - \beta \cdot \operatorname{erf}\left(\frac{T - T_g}{\sigma_g \cdot \sqrt{2}}\right) \qquad (2)$$

where ε is the tensile stroke, T is the temperature of the wire, T_g is the glass transition temperature of the nylon, and $\alpha, \gamma,$ and β are constants determined by the spring coil index.

The nylon is plated with silver that allows it to conduct current. The silver creates a non-negligible resistance along the length of the nylon which was measured to be 0.15 Ω/mm. When a voltage is applied Joule heating occurs at causes the temperature of the wire to increase. Previous research has shown that a simple thermo electric model can be used to characterize the actuator temperature. This model is defined as [12]:

$$C\frac{dT}{dt} = \frac{V^2}{R} - \Lambda(T - T_{amb}) \qquad (3)$$

where C is the thermal mass of the nylon, V is the applied voltage, R is the resistance of the nylon, Λ is the absolute thermal conductivity of the actuator, T is the temperature of the nylon and T_{amb} is the ambient temperature. The absolute thermal conductivity will change depending on the size of the actuator, the nylon wrapping configuration and the environment the actuator is operating in.

4.2. Silicone Material Model

The actuators were fabricated using Silicone TC-5005 from BJB Enterprises, which exhibits non-linear behavior during large mechanical deformations [19]. Previous studies have shown that an incompressible Ogden model can accurately predict the deformation behavior of Silicone TC-5005 [135]. The stretch ratio of silicone is defined as [135]:

$$\lambda_i = \frac{x_i}{X_i} \tag{4}$$

where λ_i is the stretch ratio in the ith direction, x_i is the final length, and X_i is the original length in the ith direction. The strain energy density function is then determined as a function of the stretch ratios, and c. The strain energy can be shown as [135]:

$$W = \sum_{i}^{N} \frac{\mu_i}{\alpha_i} (\lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3) \tag{5}$$

where W is the strain energy density, λ_i is the stretch ratio in the ith direction, α_i and μ_i are Ogden parameters, and N represents the degree of the model used. For TC5005, N = 2 gives the best results [135]. The Cauchy stress can then be obtained by taking the derivative of the strain energy density function, as [135]:

$$\sigma_i = p + \lambda_i \frac{\partial W}{\partial \lambda_i} \quad (6)$$

where σ_i is the Cauchy stress, p is the hydrostatic pressure, λ_i is the stretch ratio in the ith direction, and W is the strain energy density.

The actuator design described above uses air as the internal fluid. For air at room temperature or above and atmospheric pressure, the ideal gas law can be used to relate the volume change to pressure change. Assuming constant temperature, the change in volume of the internal chamber can be related to the pressure using Boyle's law, as [136]:

$$P_2 = P_1 \frac{V_1}{V_2} \quad (7)$$

where P_1 and V_1 are the initial pressure and volume in the chamber, while P_2 and V_2 are the pressure and volume in the chamber during actuation.

The volume of the internal chamber is compressed by the tensile contraction of the nylon and can be calculated as shown in Equation 7. The actuator is constrained in the axial direction. As a result, it is assumed that the length of the actuator remains constant during the nylon contraction. Per the nylon thermo-electric model, the nylon tensile stroke is related to the wire temperature. This tensile stroke can also be related to the volume change as shown above.

$$\frac{V_1}{V_2} = \frac{1}{(1 - \varepsilon)^2} \quad (8)$$

where ε is tensile stroke in the nylon described by Equation 1.

According to the nylon thermo-electric model, the nylon tensile stroke is a function of temperature, but remains constant with increasing stress up to the tensile strength [137]. Using the silicone material model, and the internal pressure model derived above, the stress in the nylon can be calculated to verify that it remains below the maximum tensile strength.

To calculate the stress in the nylon, a force balance was conducted between the internal pressure in the actuator, the material stress in the silicone, and the tensile stress in the nylon.

$$\sigma_n A_n = \int P\, dA + \int S_\theta dA_s \tag{9}$$

The material stresses can be calculated using the Ogden model shown above. The three principal stresses exist in the radial, circumferential, and axial directions. The stretch ratios in the axial and circumferential direction can be found based on the tensile stroke of the nylon. Assuming that the silicone is incompressible [135], the stretch ratios can be found as [138]:

$$\lambda_l = 1 \tag{8}$$

$$\lambda_\theta = 1 - \varepsilon \tag{9}$$

$$\lambda_r = \frac{1}{\lambda_l \lambda_\theta} \tag{10}$$

where λ_l, λ_θ, and λ_r represent the stretch ratios in the axial, circumferential, and radial directions, respectively. ϵ represents the nylon tensile stroke.

4.3. Quasi-static Modelling

Based on the work of Polygerinos et al. in [129], an analytical model was developed that captures the relationship between the internal pressure in the actuator and the actuator bending angle. Polygerinos et al. showed that the internal pressure in the actuator and the stress in the actuator materials resulted in opposing bending moments as [129]:

$$M_a = M_\theta \quad (11)$$

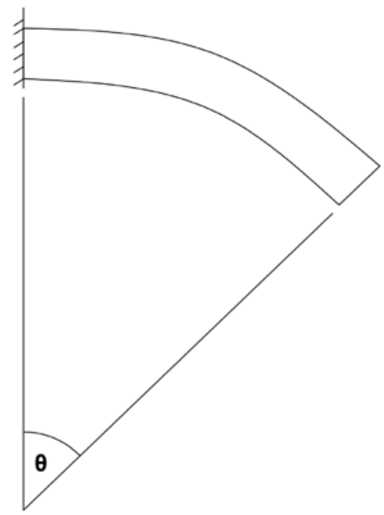
where $\boldsymbol{M_a}$ represents moments produced by the internal pressure and $\boldsymbol{M_\theta}$ represents the bending moment produced by the material stresses. The moment produced by the internal pressure can be calculated as: [129]

$$M_a = 2(P_1 - P_a) \int_0^{\pi/2} (a \sin\phi \; b) a^2 \cos^2\phi \; d\phi \quad (12)$$

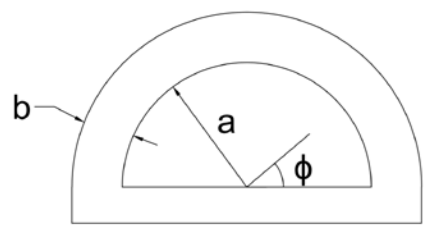
where P_1 is the internal pressure, P_{atm} is the atmospheric pressure, a, b and ϕ are shown in Figure 16. The moments generated by the material stresses can be found by evaluating Equation 13 [129]:

$$M_\theta = \int_0^b S_\beta (2a + t) L_\beta d\beta + 2 \int_{A_m} S_{\tau,\phi} ((a + \tau)^2 sin\phi + b(a + \tau) L \; d\phi) d\tau \quad (13)$$

where M_θ is the moment generated by the material stress, S_B is the material stress in the base of the actuator and $S_{\tau,\phi}$ is the stress in the hemi-cylindrical section of the actuator. The material stresses are calculated using Equation 5. An analytical solution could not be derived for Equation 13 so it was solved numerically.



(a)



(b)

Figure 16 (a) The measured actuator bending angle (b) A cross section view of the actuator with labelled dimensions. Reproduced from [15]

The analytical model derived in Equation 13 can be extended to produce and expression for the actuator force. If the actuator is constrained to a zero-bending angle, no internal bending moments are generated during pressurizations. Therefore, the torque from the actuator base can be calculated as [129]:

$$Mf \ = FLf = M_a = \frac{(4a^3 + 3\pi a^2 b)}{6} P_{in} \qquad (14)$$

where F is the contact force at the actuator tip, L_f is the actuator length, and M_f is the external bending torque generated by the contact force around the actuator base. This equation describes the relationship between pressure and force under a constant bending angle [129]. Although Equation 14 is only applicable for a bending angle of zero degrees, it follows that under constant pressure, the force output will decrease as the bending angle increases. This is due to the fact that larger moments are required to bend the actuator. Therefore, Equation 14 defines the maximum force output for a given input pressure.

Chapter 5. Experimental Results

This chapter outlines the results from testing an early stage prototype of the proposed actuator. The presented materials are toward fulfillment of the third objective of the thesis; verify the proposed model; and partially addresses objective 4; characterize the performance of the proposed fluidic actuator. The entirety of the chapter is an excerpt from section 3 of the article published in *L. Sutton and C. Menon “Design of a soft fluidic actuator using nylon artificial muscles,” Engineering Research Express Accepted June 2019.*

5.1. Internal Pressure Model Validation

Experiments were conducted to verify the internal pressure model. Three variations of the actuator were fabricated and each was tested four times by applying a voltage to the nylon. The actuator was activated using an adjustable power supply, the pressure was monitored using an pressure sensor placed on the inside of the fluid bladder and the temperature of the nylon was monitored using a Texas Instruments LMT01LPG sensor. The sensors were connected to an arduino and recorded using a data acquisition program written in Python running on a 2015 Macbook pro.

The temperature of the nylon was measured and related to the nylon tensile stroke using Equation 2 [134]. Figure 17 shows the relation between the nylon tensile stroke and the actuator internal pressure. Good correlation between the theoretical and experimental results was observed, demonstrating the validity of Equation 7.

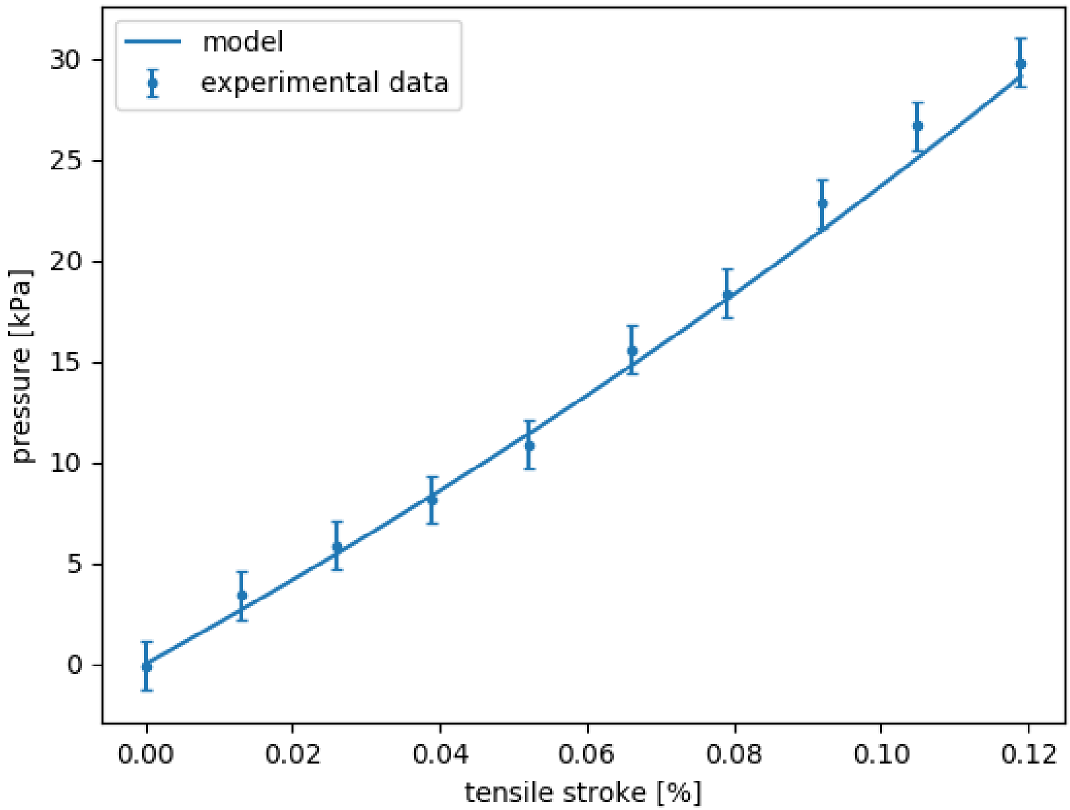


Figure 17 Internal pressure versus nylon tensile stroke plotted against the analytics model. Reproduced from [15]

5.2. Position Model Validation

Six variations of the actuator design were fabricated and tested to verify the position model. Each actuator was tested four times by applying a range of voltages to the nylon wires while the motion of the actuator was recorded. The pressure of the actuator was monitored using the configuration described in 5.1. The position was later determined in the post processing step using the colour marker attached to the end of the actuator. The bending trajectories of the actuator compared to the analytical models are illustrated in Figure 18 - Figure 20. A close correlation can be observed between the theoretical model and the experimental data. A maximum displacement error of 4.2% was calculated demonstrating the validity of the models.

Small discrepancies can be seen in the pressure values due to initial prebending and gravitational influences. This resulted in a pressure error of 8.3%.

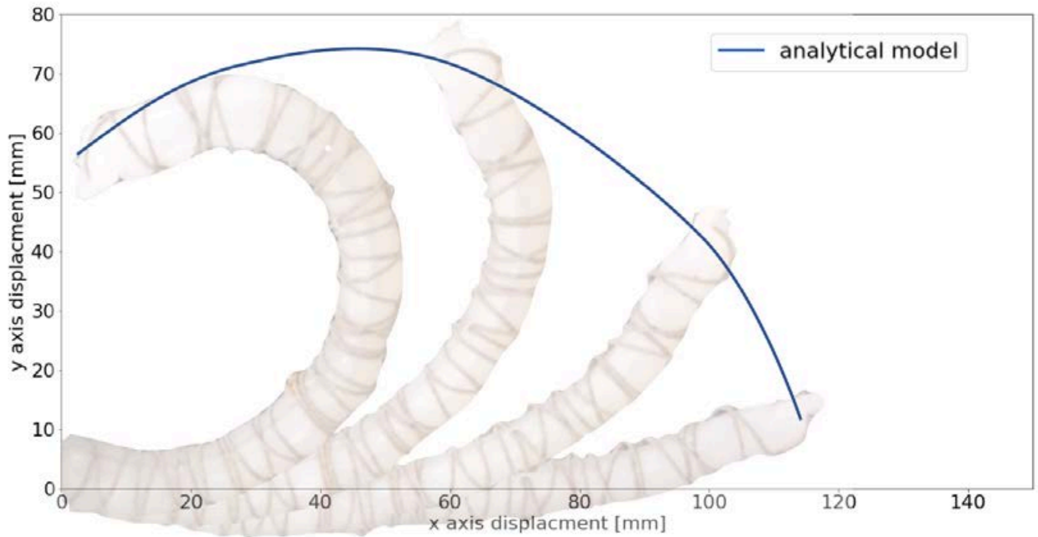


Figure 18 Actuator analytical model visualized against a bending actuator. Reproduced from [15]

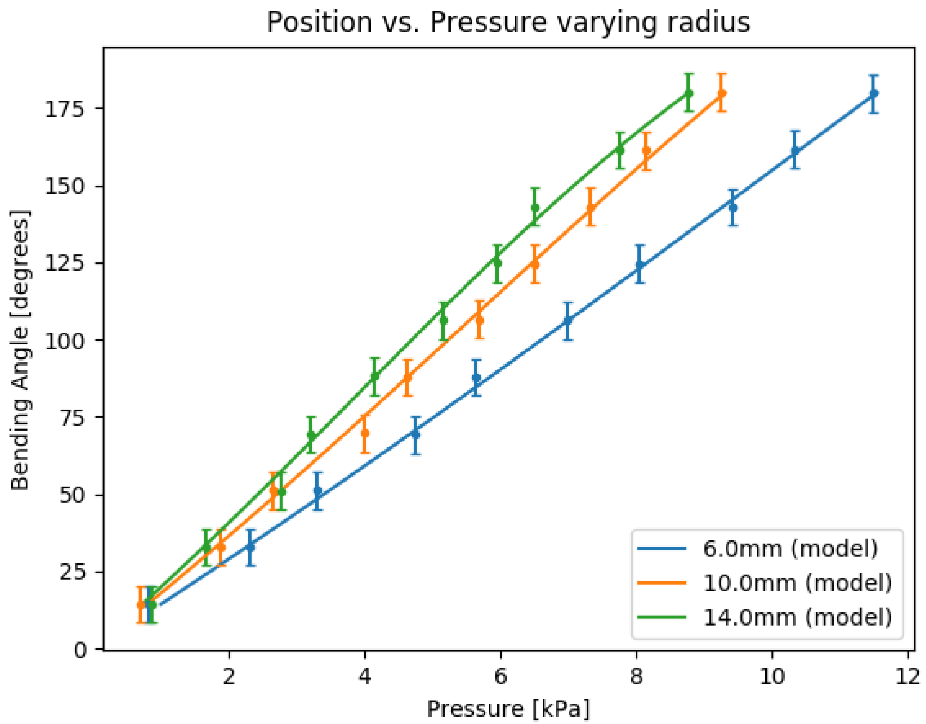


Figure 19 Bending angle versus pressure, for radius values ranging from 6.0 to 14.0mm. Reproduced from [15]

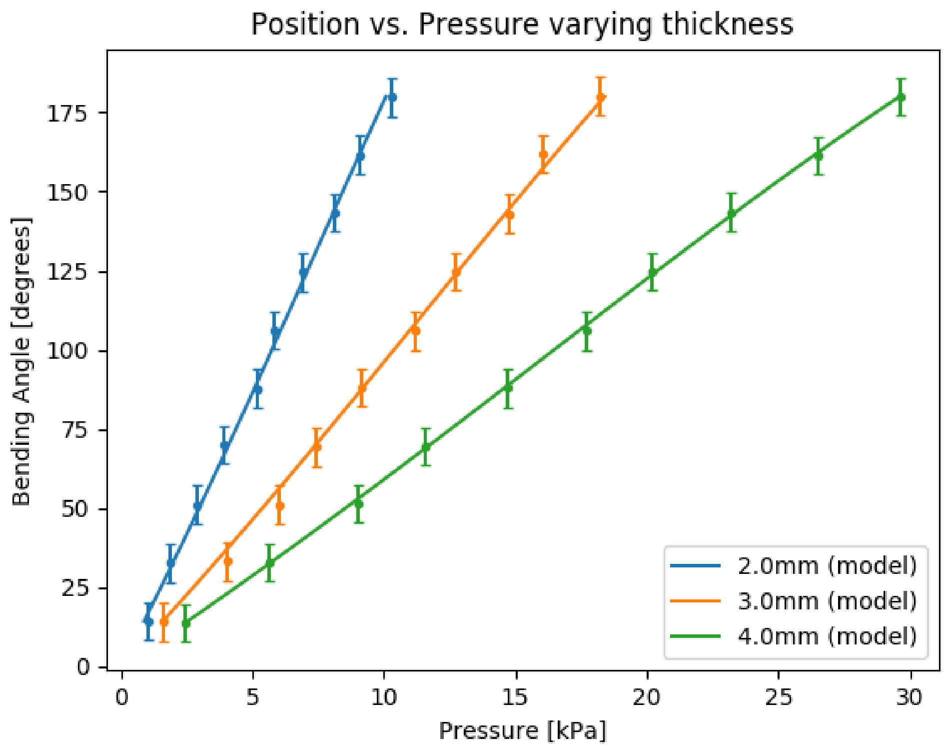


Figure 20. Bending angle versus pressure, for wall thickness ranging from 1.0 to 4.0mm. Reproduced from [15]

5.3. Force Model Validation

To verify the force model, experimental results were obtained by examining six variations of the actuator design. A range of voltages was applied to the nylon actuators and the force was measured at the actuator tip as shown in Figure 21. The top layer of the actuator was fixed to prevent the actuator from bending during pressurization.

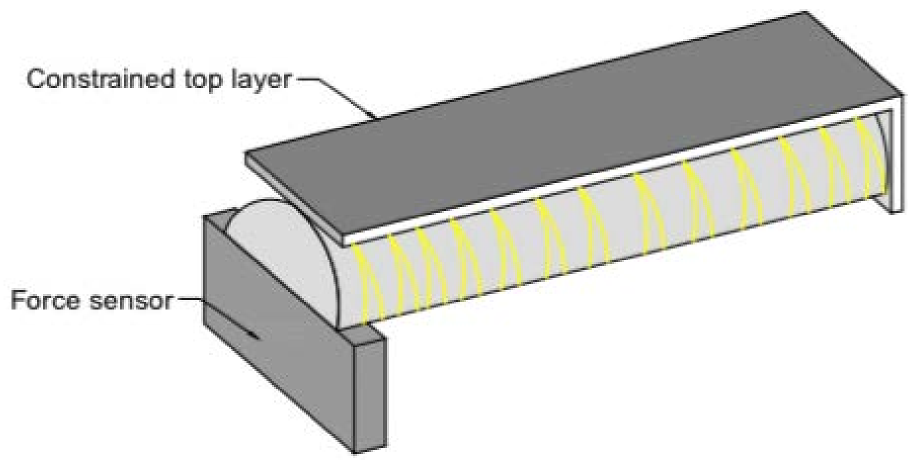


Figure 21 Actuator force measured with the top layer constrained

The forces at the tip of the actuator compared to the analytical models are shown in **Error! Reference source not found.** – Figure 23. The experimental results show a close correlation with the predicted force at the tip of the actuator for this configuration. A maximum displacement error of 5.3% was calculated demonstrating the validity of the models. Small discrepancies can be seen in the pressure values due to initial prebending and gravitational influences.

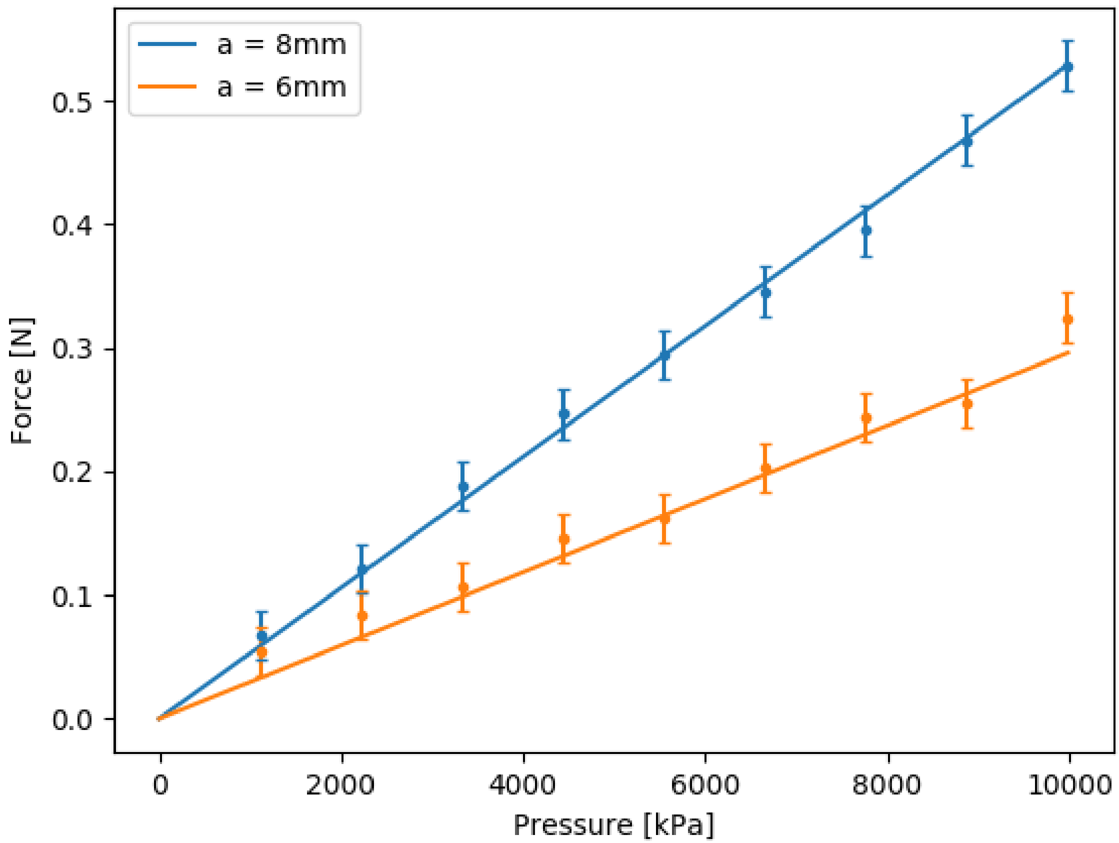


Figure 22 Force measurements of the actuator versus internal pressure for various radii. Reproduced from [15]

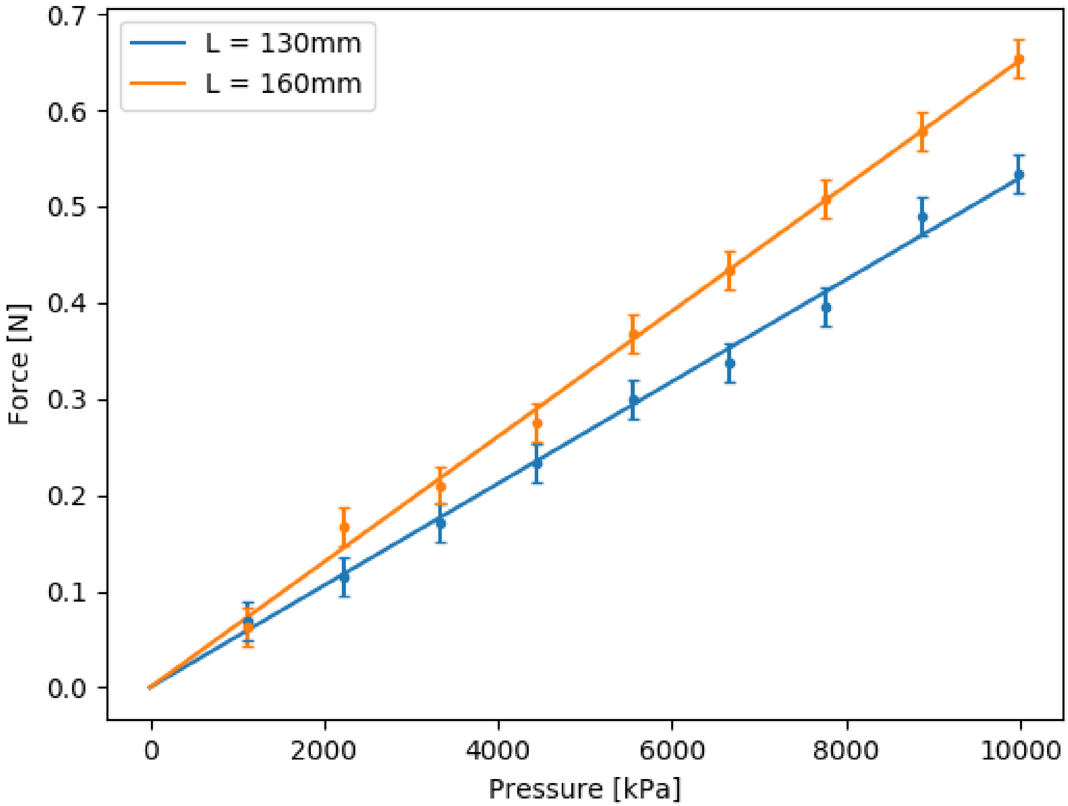


Figure 23 Force measurements of the actuator versus internal pressure for various actuator lengths. Reproduced from [15]

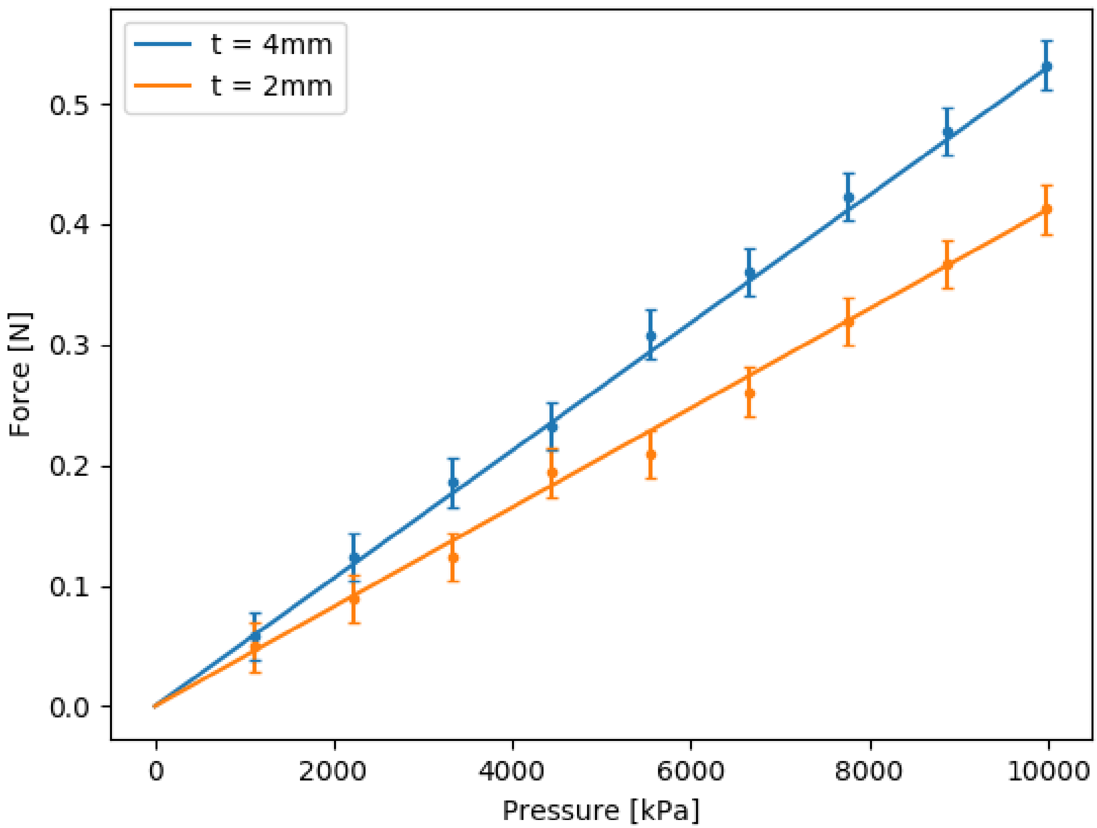


Figure 24 Actuator forces versus internal pressure for various actuator wall thicknesses. Reproduced from [15]

5.4. Position Controller

Using the analytical model developed above, a position controller was developed to demonstrate the simplicity at which the proposed actuator may be controlled. A feedback control loop with an angle filter, as shown in Figure 26, was implemented to demonstrate the ability of the analytical model of Equation 13 to use pressure information to estimate bending angle in real time. Although the input to the system is voltage, the variation in the size of the actuator, and the ambient temperature affects the heating and cooling rate of the nylon. As a result, voltage provides an unreliable input to the feedback controller. Alternatively, the internal air pressure is relatively simple to measure in real time and is a good predictor of the actuator bending angle as shown in Figure 20. In addition, utilizing pressure as the input to the feedback control loop, makes the controller more versatile as it can be used in more operating environments. To control the power input to the nylon, a simple bang bang controller was utilized due to the slow cooling rate of the actuator. The pressure for the actuator was monitored using the configuration described in section 5.1. The power input to each actuator was modulated using a RFP30N06LE MOSFET connected to an Arduino Mega (Figure 25).

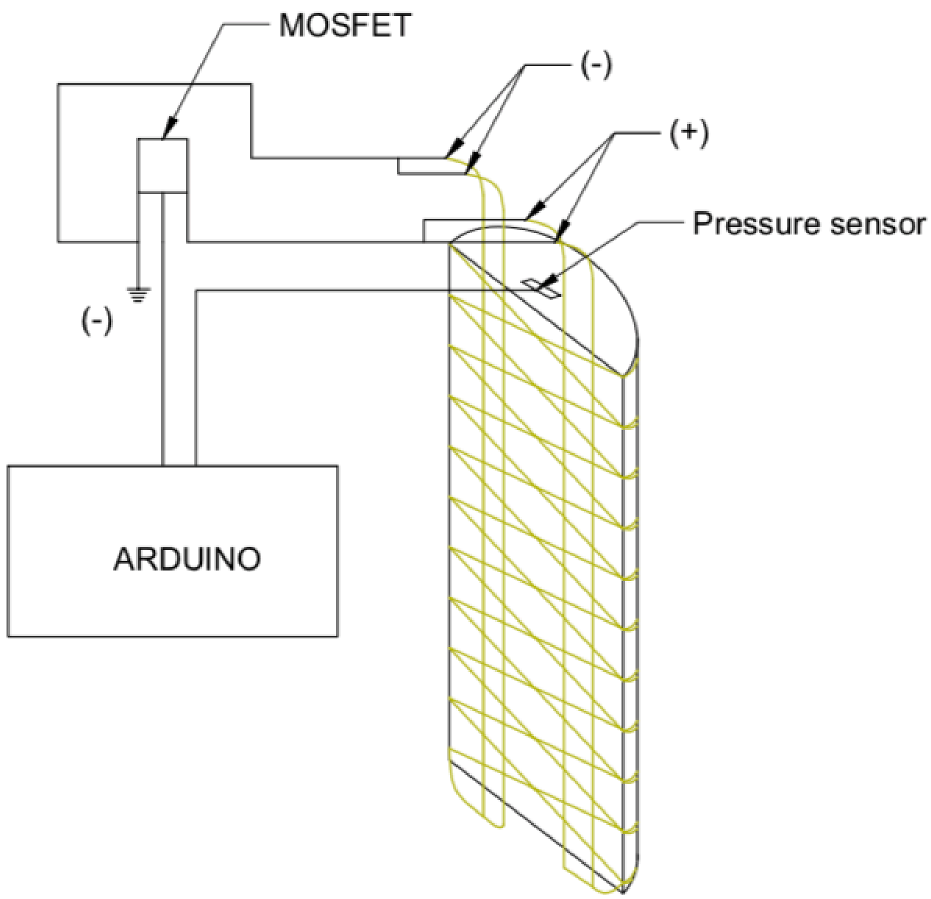


Figure 25 Schematic of control system for each actuator. Each actuator was equipped with a pressure sensor and the power was modulated to the nylon using a RFP30N06LE MOSFET.

The feedback control loop was tested against a sinusoidal reference angle and a step response reference angle. The controller was successful in tracking an angle signal of 0.04 Hz as shown in Figure 27 and Figure 28. The maximum applied power to the actuator was 1.92W (12V, 160mA). A larger power input could also be used which would reduce the actuator heating times, however, the cooling time is limited by the natural convection.

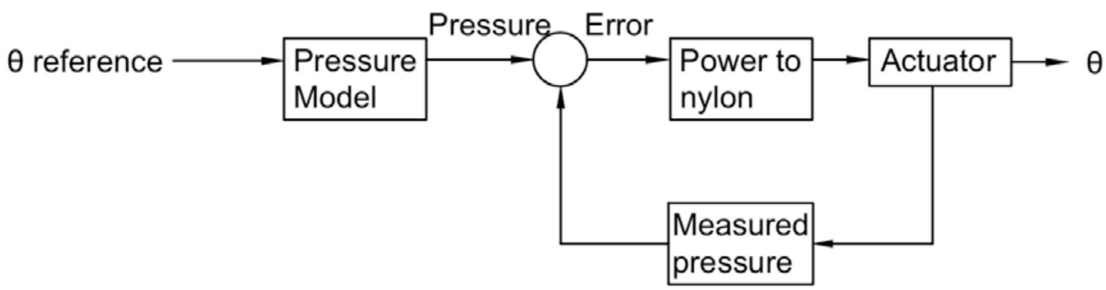


Figure 26 Schematic of the closed loop controller for actuator bending angle. Reproduced from [15]

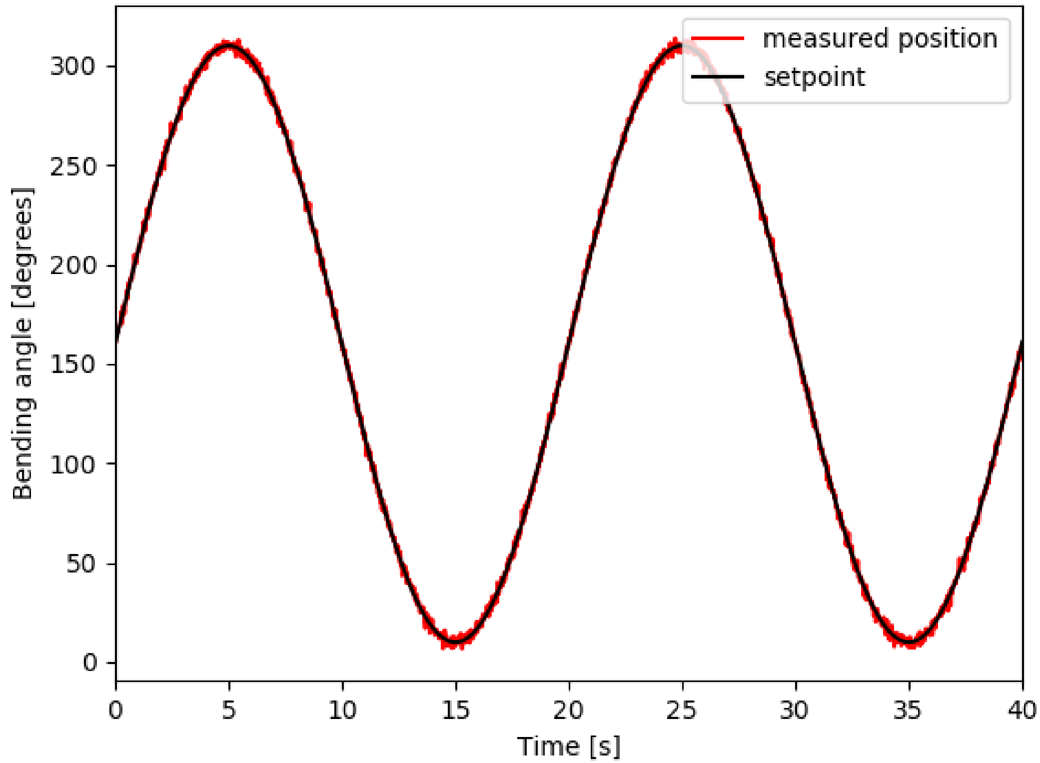


Figure 27 Feedback control loop performance. Actuator tracking a sinusoidal reference angle with a period of 0.04Hz. Reproduced from [15]

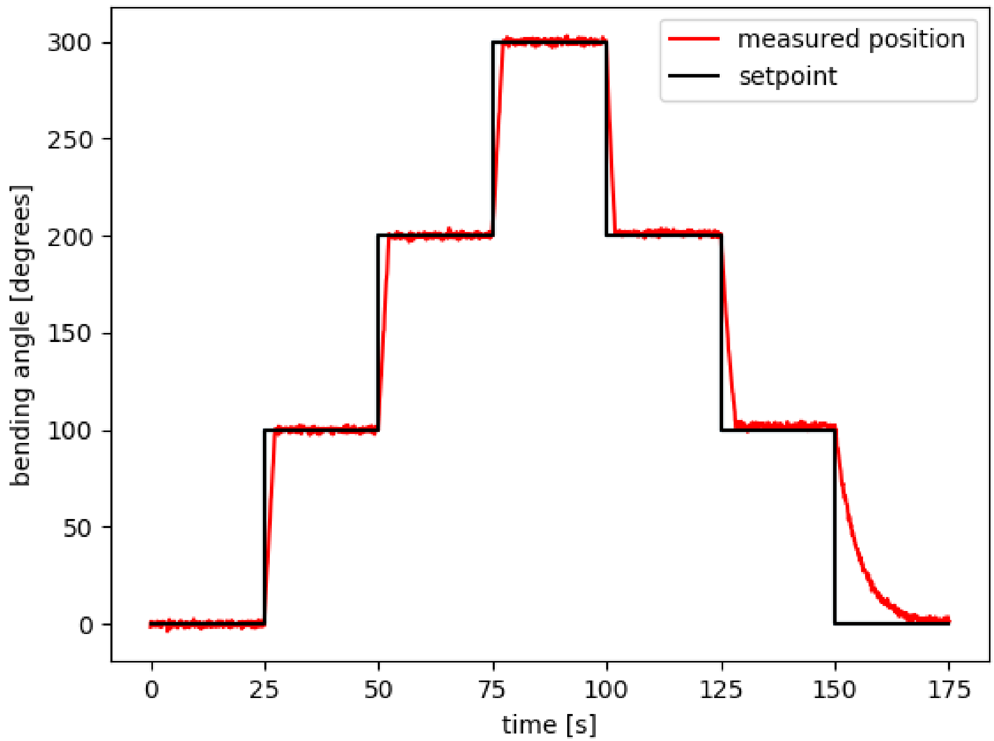


Figure 28 Feedback control loop performance. Step response of the actuator controller. Reproduced from [15]

5.5. Soft Gripper Demonstration

In order to provide evidence of the potential ability of the soft actuator to be used in robotic applications, a prototype of a soft robotic gripper (Figure 30) was constructed. Three actuators were mounted in a holding structure fabricated in ABS via a 3D printer. The power input to each actuator was modulated using a RFP30N06LE MOSFET as shown in Figure 25 connected to an Arduino Mega (Figure 29).The pressure for each actuator was also monitored and connected to an arduino similar to the configuration described in 5.1.

The gripper was powered by a single 9V battery and with each actuator drawing approximately 130mA of current. Figure 31 shows the pressure in the actuators during the grasping motion. Figure 30 shows the gripper grasping a ping pong ball through all stages of grapsing. Figure 31 shows that the gripper was able to grasp various objects. Each actuator could be manipulated individually, and there was no noticeable crosstalk between actuators caused by convective heating. Since the gripper is made out of a soft polymer and the actuation system is soft there is potential for this system to grasp delicate objects as similar configurations have demonstrated this capability [139] [140] [141] [142] [143].

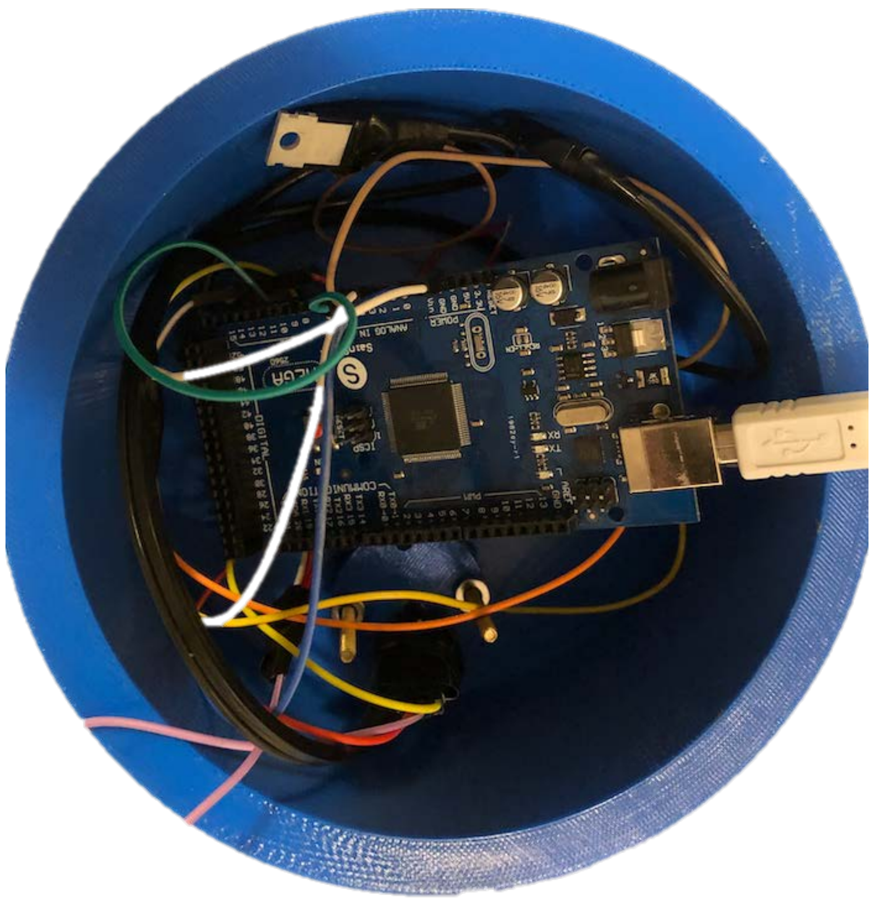


Figure 29 Top down view of the internals of the gripper demonstration. Each actautor is equipped with a pressure sensor which is connected to an arduino mega. The power to each actuator is modulated using a RFP30N06LE MOSFET controlled by the arduino.

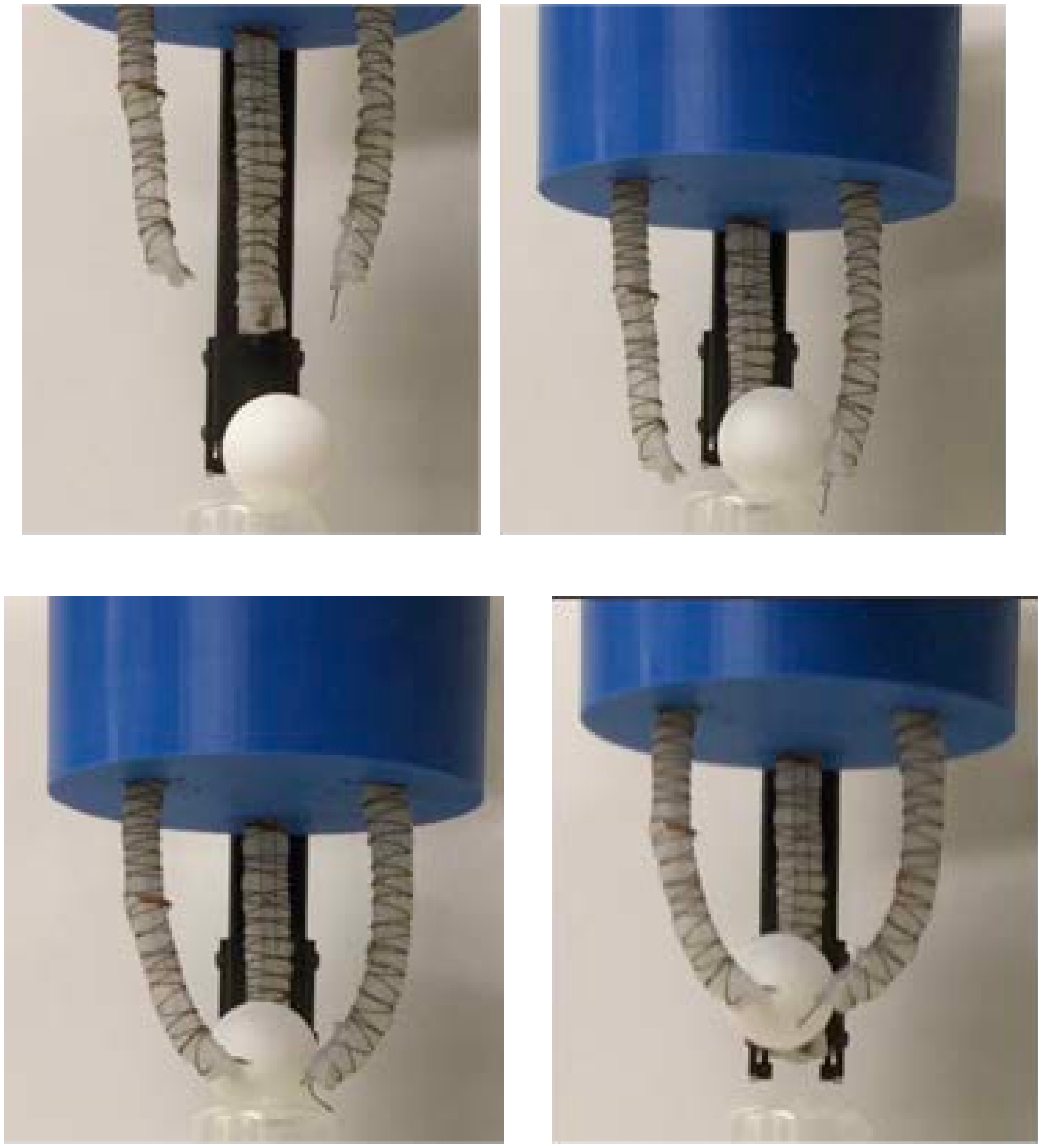


Figure 30 Soft gripper demonstration. The soft gripper shown grasping a ping pong ball through all stages of grasping. Reproduced from [15]

Figure 31 The soft gripper shown grasping various objects.

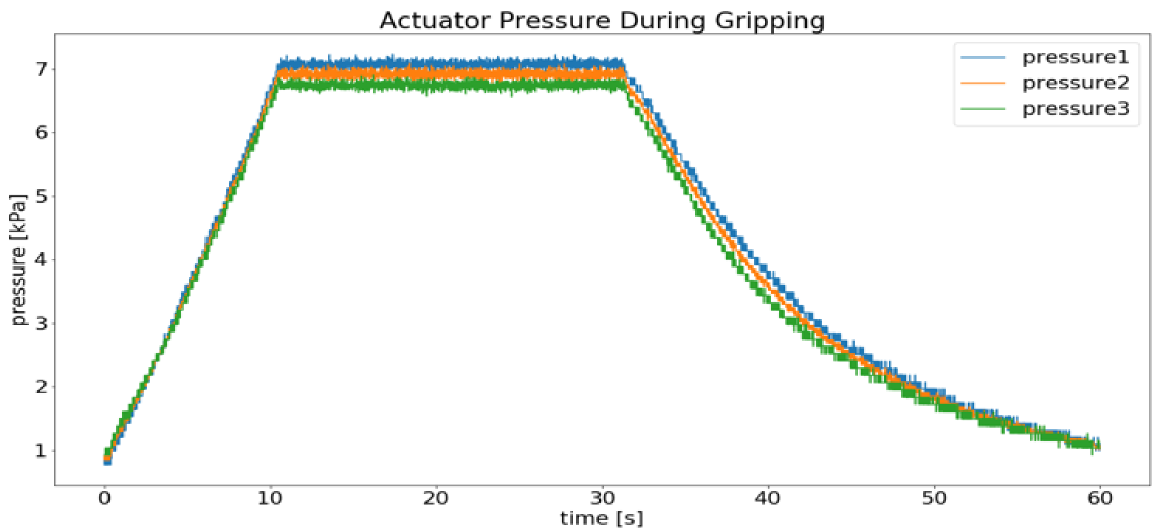


Figure 32 Plot of pressure versus time for the actuators in the gripper

Chapter 6. Design Considerations

This chapter uses the analytical models developed in chapter 4 to outline a set of design considerations for the proposed actuator. The presented materials are here in combination with the material from chapter 5 are aimed towards fulfillment of the fourth objective of the thesis; characterize the performance of the proposed fluidic actuator. The entirety of the chapter is an excerpt from section 3 and section 4 of the article published in *L. Sutton and C. Menon “Design of a soft fluidic actuator using nylon artificial muscles,” Engineering Research Express Accepted June 2019.*

The proposed fluidic actuator may be suitable for applications where pressure driven actuators are currently used. However, the size and forces generated by the actuator are limited by the capabilities of the nylon artificial muscles. It is important for the robotics designer to understand how these limitations affect the actuator’s capabilities. Using the models developed above, a set of theoretical limits could be calculated based on the physical dimensions of the actuator to establish the maximum achievable torques and maximum actuator dimensions for a full range of motion.

6.1. Nylon Limitations

According to Equation 7, the stress in the nylon is proportional to the forces generated by the internal pressure and material stresses in the actuator walls. Furthermore, the nylon tensile stroke is a function of the temperature only and is independent of the tensile stress as long as the tensile stress remains below the ultimate tensile strength of the nylon [133]. Using the tensile stroke, the internal pressure in the actuator can be calculated using Equation 8 and the material stresses in the actuator can be calculated using Equation 13. Based on the calculated pressure and material stresses, the stress in the nylon can be calculated using Equation 8. It is assumed that this force is evenly distributed over the number of nylon coils which can be calculated based on the wrapping angle (Figure 33) and the width of the nylon. The force in the nylon is then checked to remain below the ultimate tensile strength. Furthermore, Haines et al showed that the nylon ultimate tensile strength and the tensile stroke is dependent on the nylon coil index and that an inverse relationship exists between the nylon ultimate tensile strength and the maximum tensile stroke. The results are summarized in Figures Figure 34 -

Figure 36.

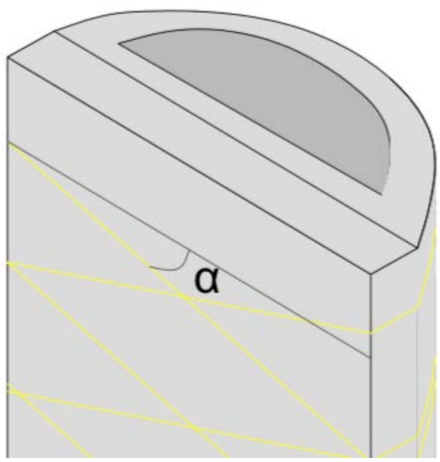


Figure 33 Depiction of the nylon wrapping angle

Figure 34 shows how the actuator dimensions affect the tensile force generated in the nylon. As the actuator dimensions increase, the force required to compress the actuator walls increases beyond the maximum capabilities of the nylon. The nylon limitations for various coil indices are shown with a dashed black line.

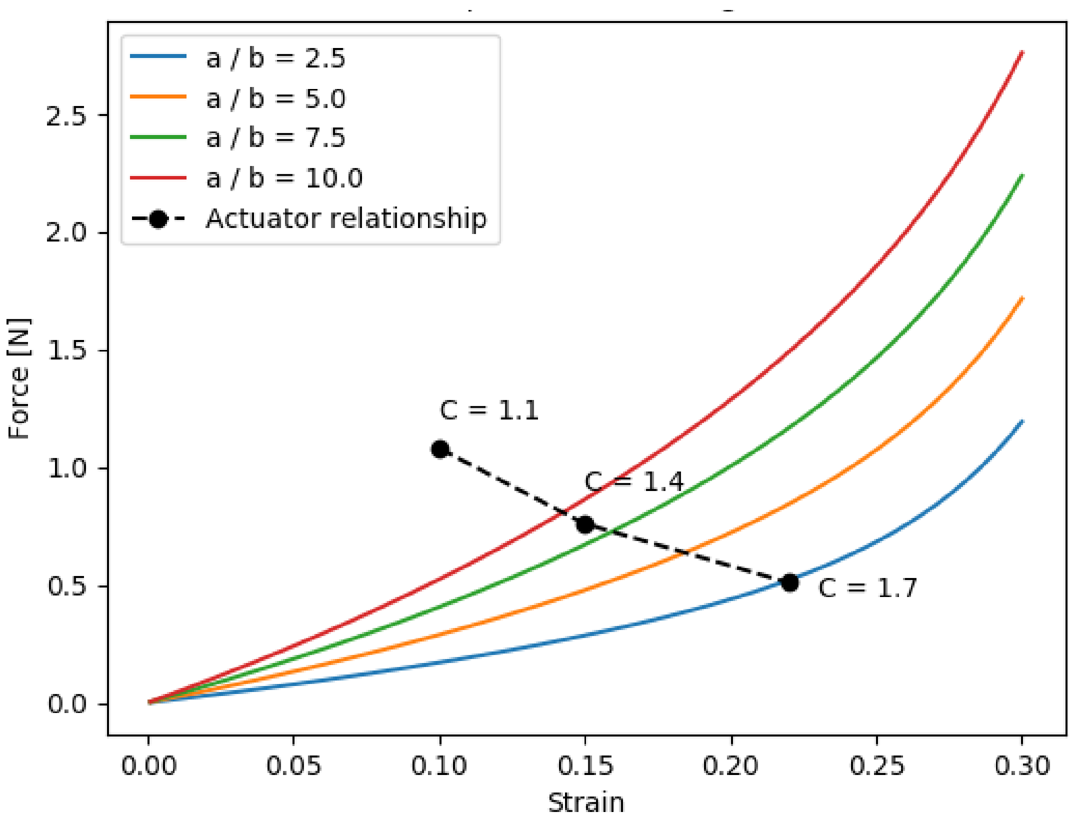


Figure 34 Forces in the nylon versus. tensile stroke for various actuator dimensions

6.2. Maximum Achievable Torque

Using the results of Figure 34, the maximum achievable torque for a proposed actuator can be calculated given the actuator dimensions and the nylon coil index (Equation 14). The nylon thresholds for various wrapping angles were determined using Equation 8 and are shown as a dashed black line. From Figure 35 it can be observed that a larger coil index produces a larger torque for smaller actuator dimensions. However, as the actuator dimensions increase, the nylon quickly reaches its limitations. In addition, by increasing the wrapping angle, the expansion force generated by the internal pressure and materials stresses is distributed over less nylon coils. As a result, the maximum force in the nylon is reached sooner for actuators of the same dimensions.

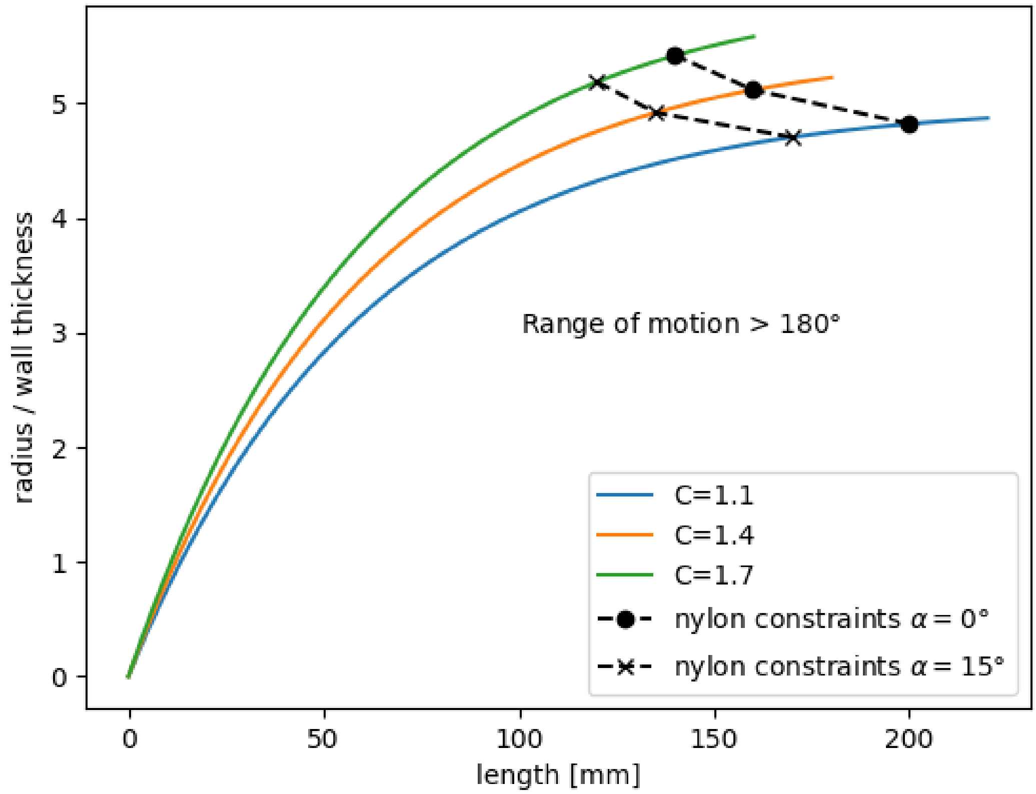


Figure 35 Maximum achievable torques for versus actuator dimensions. Actuator limitations shown as a dashed black line

Range of motion

Figure 36 summarizes the theoretical limits for the bending angle of the proposed actuator. The bending angle was calculated using Equation 13 and Equation 8 was used to determine the bending angle limitations. Given an actuator and its dimensions, using

Figure 36 the designer can determine if the actuator can undergo a full range of motion. As the actuator dimensions increase, the stress in the nylon increases causing the range of motion to decrease. Similar to the maximum torque, by increasing the wrapping angle, the expansion force generated by the internal pressure and materials stresses is distributed over less nylon coils. As a result, the maximum force in the nylon is reached sooner for actuators of the same dimensions.

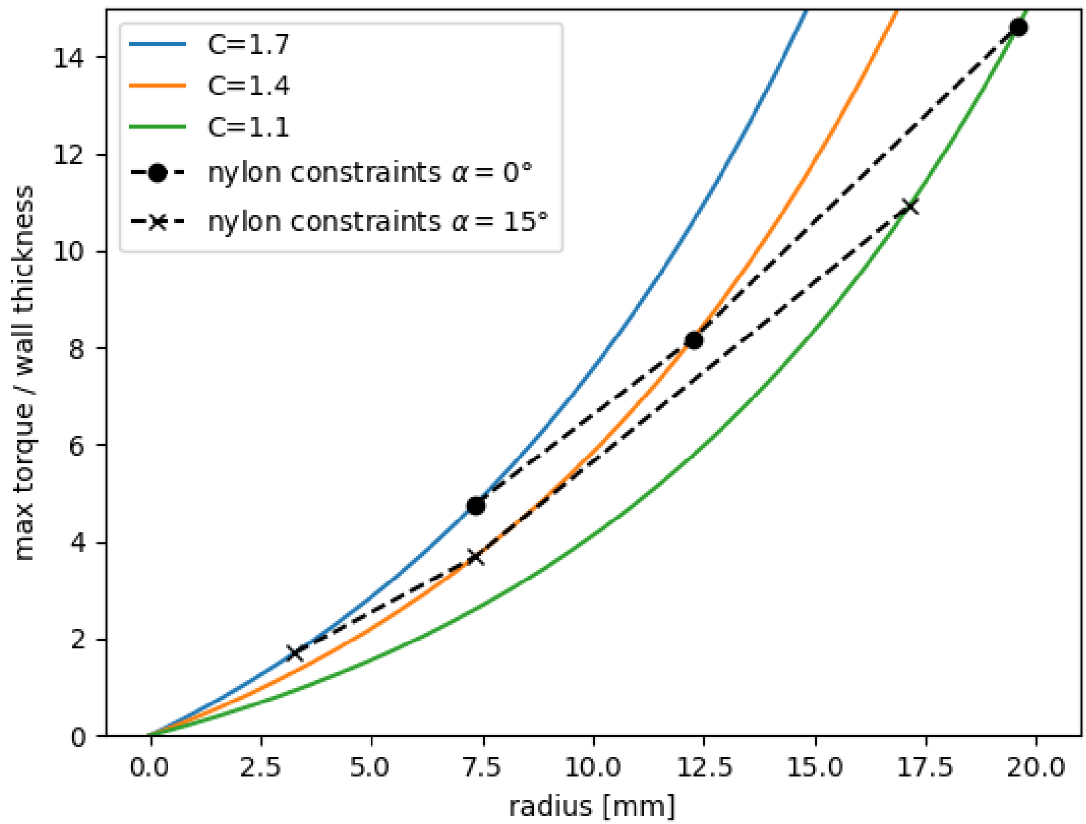


Figure 36 Maximum achievable range of motion versus actuator dimensions. Actuator limitations shown as a black dashed line.

Using the results of Figures Figure 34 -

Figure 36, a robotics designer with higher force requirements might consider using the maximum radius 20mm with a nylon coil index of 1.1 (Figure 35).The designer could select a large but reasonable wall thickness of 6mm and a length of 90mm. According to Figure 35, this actuator could produce a maximum force of 1.2N. The resulting actuator could also undergo a full range of motion according to

Figure 36.On the contrary, another robotics application may have smaller force requirements but the actuator is space constraint. An actuator with a radius of 7.5mm,

length of 70mm and a wall thickness of 2mm can produce a maximum force of 0.15N if nylon with a coil index of 1.7 is used.

Chapter 7. Discussion

The entirety of the chapter is an excerpt from section 5 of the article published in *L. Sutton and C. Menon Design of a soft fluidic actuator using nylon artificial muscles," Engineering Research Express Accepted June 2019.*

Soft fluidic actuators can generate complex motions at a low mechanical cost. To date, the development of such actuators has largely relied on mechanical compressors or pumps to supply the input fluid pressure. The proposed actuator aims to bridge the gap between current fluidic actuators and a complete, compact, soft solution. By utilizing nylon actuators, the proposed fluidic actuator has no need for an external compressor or pump while still providing the benefits of a soft, compliant fluid actuator.

Depending on the application, the proposed actuators could be used with off the shelf batteries or commercially available flexible batteries to produce a completely soft portable system. For example, the gripper described above in Figure 31 used a 9V battery and drew approximately 400mA of current at maximum capacity. Flexible batteries such as those avaible from Jenax Inc. [144] could have been used for limitted amounts of time. In contrast, conventional bending fluidic actuators require both a compressor and an electrical system. Although the electrical system can be made portable or flexible, soft portable compressors are not currently available [4]. For the robotics designer looking for portable soft robotics system, the proposed actuators could potentially be suitable.

For robotics designers looking to utilize the proposed actuators, analytical models were developed to provide performance information on the actuator prior to manufacturing. The position model showed a close correlation with the experimental data. A maximum displacement error of 4.2% was calculated demonstrating the accuracy of the models. The small discrepancies were likely due to the initial bending of the actuator caused by gravitational influences. Additionally, the force model showed good correlation with the experimental results (maximum force error of 4.3%). Using the analytical models, a minimalist position controller was implemented to demonstrate how a designer might implement a control system in practice. The analytical models were also used to calculate a set of design considerations for the robotics engineer. These design plots can be used select the optimal nylon fibre and actuator dimensions to best suit the designer's requirements.

Nylon actuators offer a lightweight alternative solution to traditional actuation methods. Currently the system is limited by restricted muscle relaxation time. Thus, further research could be conducted to improve the speed of cooling the nylon. This could be done by immersing the coils in water, increasing air flow around the wire, adding heat sinks to the design, or decreasing the air temperature around the coils. Additionally, this problem could be overcome by adding opposing actuators that could compensate for the slow relaxation times. The wrapping procedure could also be improved. Currently the nylon is wrapped radially by hand as this was a preliminary research project. However, the procedure could be improved by creating an automated system. The system could rotate the silicone bladder while moving along the axis. The coiled nylon could be fed and wrapped around the bladder as it rotates. This could improve the reliability of the proposed actuators by reducing the bulging effect and potential twisting induced caused by wrapping the actuators manually.

Research in the area of soft robotics is an emerging field and nylon actuators could potentially provide a soft, lightweight, alternative to pressure driven fluidic actuators. By combining the nylon actuators with flexible power sources future studies may examine how robots can be composed of entirely soft components and remain completely self-contained.

Chapter 8. Future Work

A flexible fluidic actuator is presented which utilizes nylon artificial muscles for activation. The proposed actuator is made up of two main components, a soft fluid bladder, and artificial muscles embedded and or wrapped around the fluid bladder. The shape of the fluid bladder and the arrangement of the artificial muscles allow the actuator to deform to the desired configuration. By utilizing contractile elements, the actuator does not require a pump or compressor for actuation. Various embodiments of the actuator are proposed which may produce motions including but not limited to elongation, bending, twisting, and planar motion. The proposed fluidic actuator may be suitable for a number of applications including but not limited to surgical robots, wearable orthoses, or robotic grippers. This chapter outlines potential future directions for further development of the proposed actuator and potential applications where it may make an immediate impact.

8.1. Potential Applications

As described in Chapter 2, soft robotics is entering many new fields and new applications are being actively studied. The proposed actuator can potentially be used in a number of applications where soft these robotic actuators are currently. However, as outlined in Chapter 6. Design Considerations, the proposed actuator is most suitable for applications with certain force requirements and size constraints. Based on the results of Chapter 6, the proposed actuator has the potential to make the most immediate impact on assistive wearable devices, and locomotion robots.

The proposed actuator could be used in the design of an assistive wearable orthosis for the hand and wrist. These devices have a range of force requirements dependent on the severity of the affected extremity. Assistive devices to for the hand also have lower speed requirements [129]. The proposed device could assist in the rehabilitation process by performing the repetitive movements needed to restore functionality for stroke patients suffering from hemiparesis or hemiplegia. Studies have shown that robotic aided therapy can produce results comparable with conventional means of physical therapy [103]. The proposed therapeutic devices could be administered by physio therapists for the patient to use in the comfort of their own home, decreasing hospitalization costs and increasing the frequency of therapy for the user. A number of soft robotic devices have been used successfully for this purpose [75] [104] [105] [106] (Figure 35 and Figure 36). However, these devices currently require tethered pneumatic channels. Since the proposed device can be equipped with a portable power source and has no need for an external compressor, an assistive device built using the proposed actuator could potentially be portable and completely self-contained. Furthermore, the device could be worn to assist with activities of daily living in addition to rehabilitation purposes.

Figure 37 A soft wearable assistive device for the hand, powered by pneumatic actuators and tethered to a pneumatic compressor. Reproduced with permissions from [145]

Figure 38 (a) A soft robotic rehabilitation device for the hand. (b) A patient utilizing the device under superision of the clinician. The pump and control box required to activate the device are also depicted. Reproduced with permissions from [107]

In addition to wearable devices, the proposed actuator could potentially find use in the development of locomotive robots. As outlined in Chapter 2, soft bodied robots have enabled a number of locomotive robots. The soft locomotive robots have shown improved navigation capabilities over their rigid counterparts when exploring new terrains; examples include vertical surfaces, desert sand, rubble, and deformable surfaces such as mud and soil [76]. This could allow soft robots to be used in new operating environments for many exciting applications including, search and rescue, or environmental monitoring. However, many of the studied soft robotic systems require power and control signals delivered through pneumatic tethers since compressors are relatively heavy [24] (Figure 39 Figure 40). Furthermore, these robots typically have small force requirements and limited speed requirements depending on the application. The proposed actuator could potentially be used in place of these pneumatic actuators to create a completely soft, self-contained portable system.

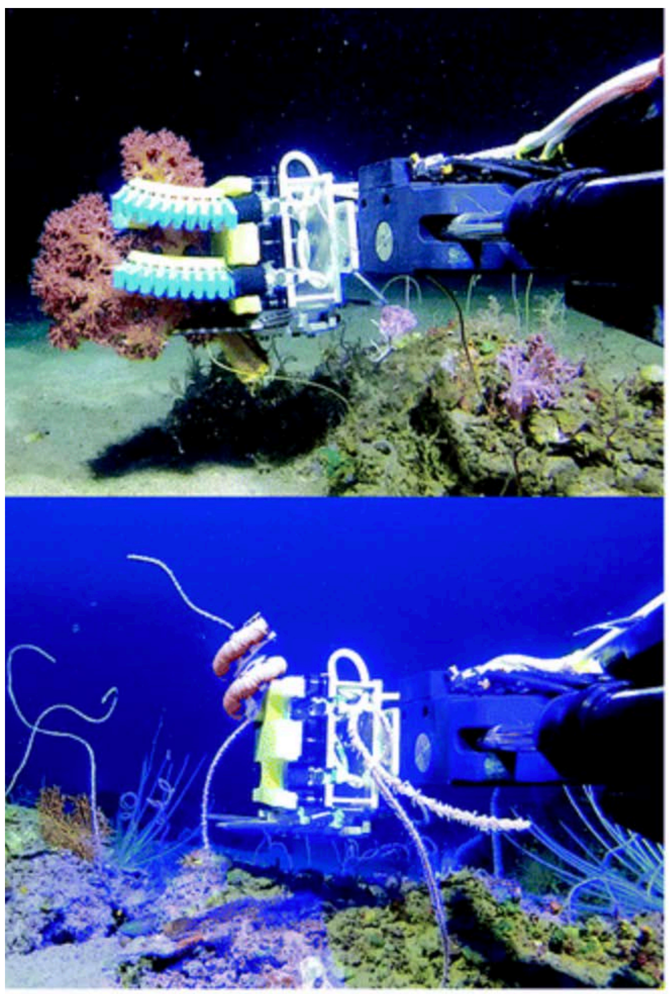


Figure 39 A soft robotic system used to sample deep coral reefs. The robot is currently limited by its tethers to its pneumatic power source. Reproduced with permissions from [146]

Figure 40 A soft robotic system used to mimic snake like locomotion for environmental monitoring purposes. The robot is currently limited by its bulky rigid pneumatic compressor. Reproduced with permissions from [147]

8.2. Actuator Development

The proposed actuator incorporates a flexible fluid bladder wrapped embedded with nylon artificial muscles. The developed actuator is configured to bend the actuator when the nylon is activated. However, the fluid bladder can take any shape, it is only dictated by the mold in which it is cast. This in combination with a unique configuration of nylon wrapped and embedded in the bladder can be used to deform the actuator to the desired shape. A variety of configurations are proposed to achieve, the following motions elongation, contraction, bending, twisting, and planar movement. Future development of the proposed actuator could explore the following actuator designs.

Figure 41 shows the arrangement of a fluidic actuator where elongation is achieved. This is achieved by wrapping the soft fluid bladder in artificial muscles. When the artificial muscles activate, the fluid bladder is compressed in the radial direction. As a result, the fluid pressure increases and acts to expand the soft bladder. The bladder is constrained in the radial direction due to the stiffness artificial muscles. However, there is no constraint in the axial direction which allows the soft bladder to expand in the axial direction.

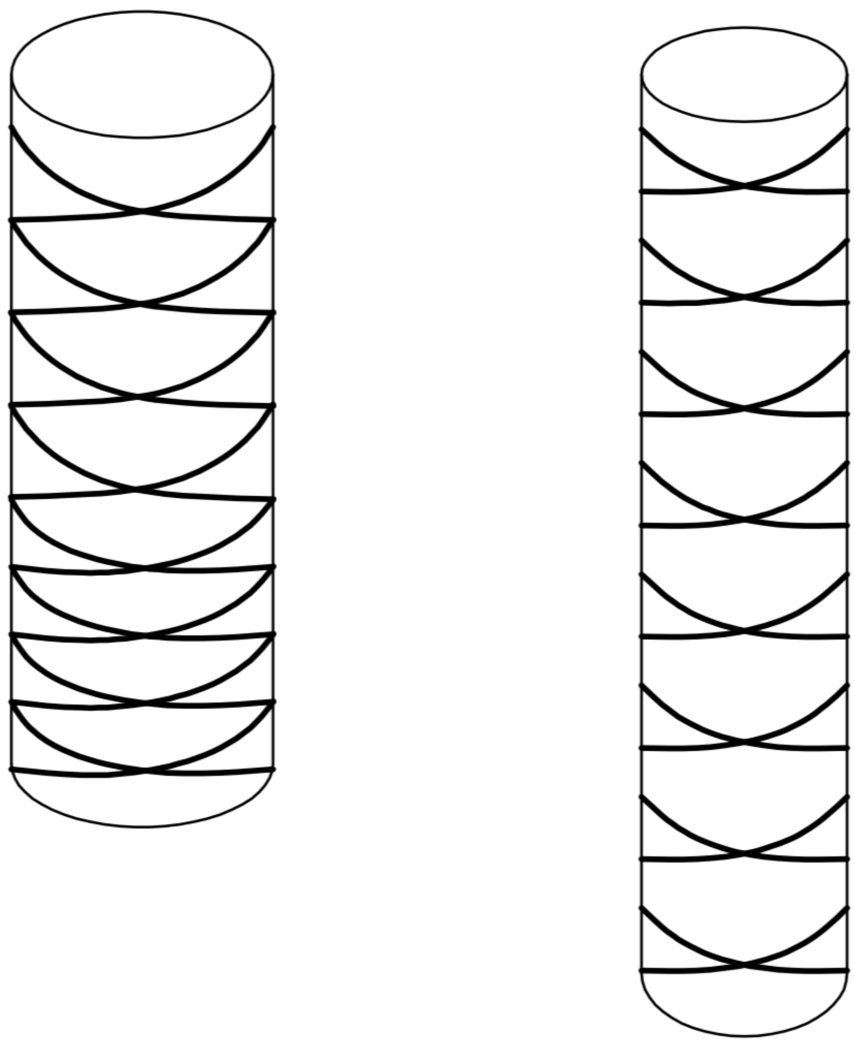


Figure 41 Perspective views of the fluidic actuator which uses artificial muscles to increase the internal pressure, elongating the actuator.

Figure 42 shows a configuration of the actuator where twisting is achieved. This may be achieved by wrapping the artificial muscles around the soft bladder in a spiral pattern.

The contraction of the muscles causes the fluid pressure to increase while also acting to provide torsion on the soft bladder around the central axis.

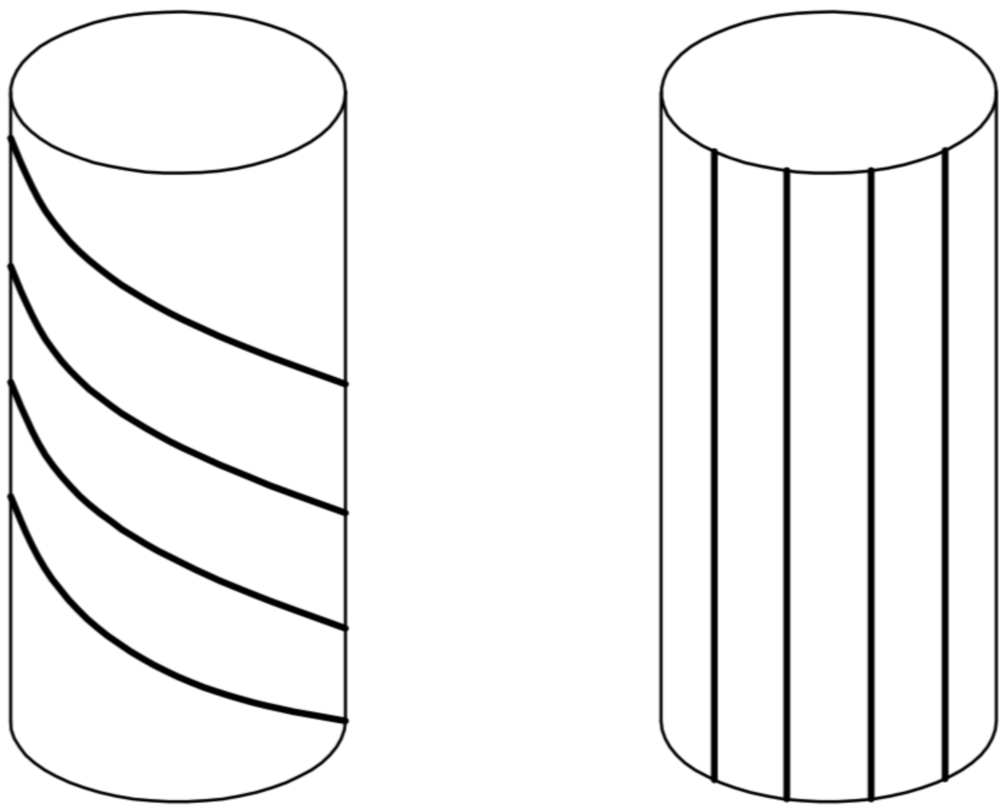


Figure 42 Perspective views of the fluidic actuator with artificial muscles arranged to twist the actuator around the central axis.

Figure 43 shows a configuration of the flexible fluidic actuator where a combination of bending and twisting is achieved. This configuration uses the same fundamental principles described for Figure 13 to achieve bending. However, the radial muscles are arranged in an asymmetric spiral pattern around the fluid bladder**.** In addition, an asymmetric backbone is added to actuator to further increase twisting.

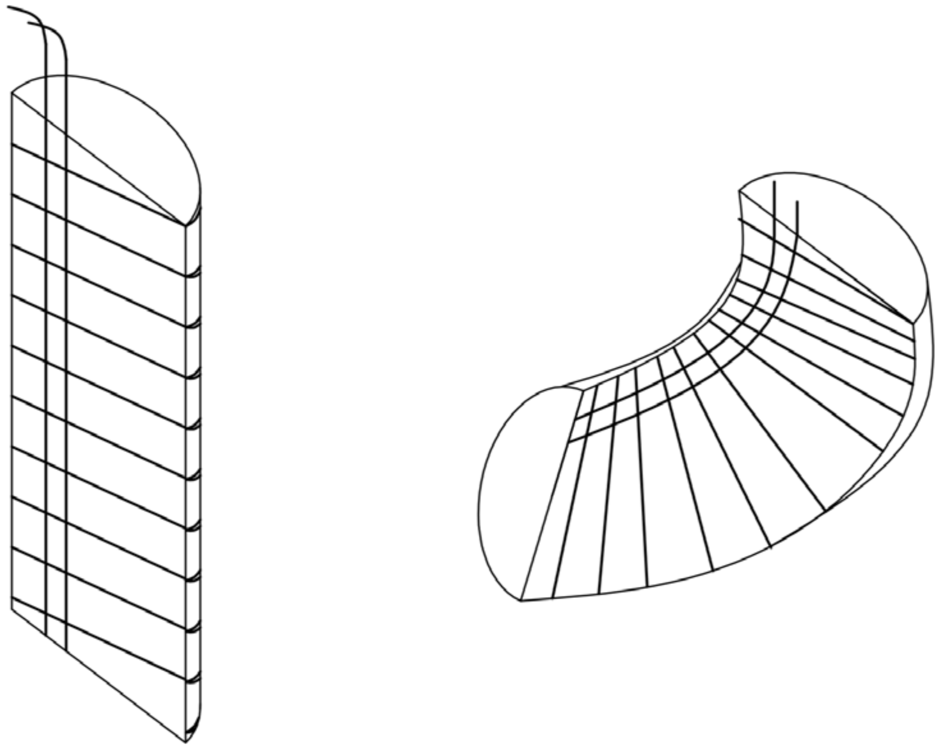


Figure 43 Illustration of a bending fluidic actuator with actuators arranged to bend and twist the actuator.

Figure 44 shows a further embodiment of the configuration proposed in Figure 43 where a combination of bending and twisting is achieved. This configuration uses the same fundamental principles described for Figure 43 to achieve bending and twisting. However, the axial muscles are activated individually to achieve twisting in both directions. The proposed configuration may be useful for not only grasping but also for manipulating the object after it has been grasped.

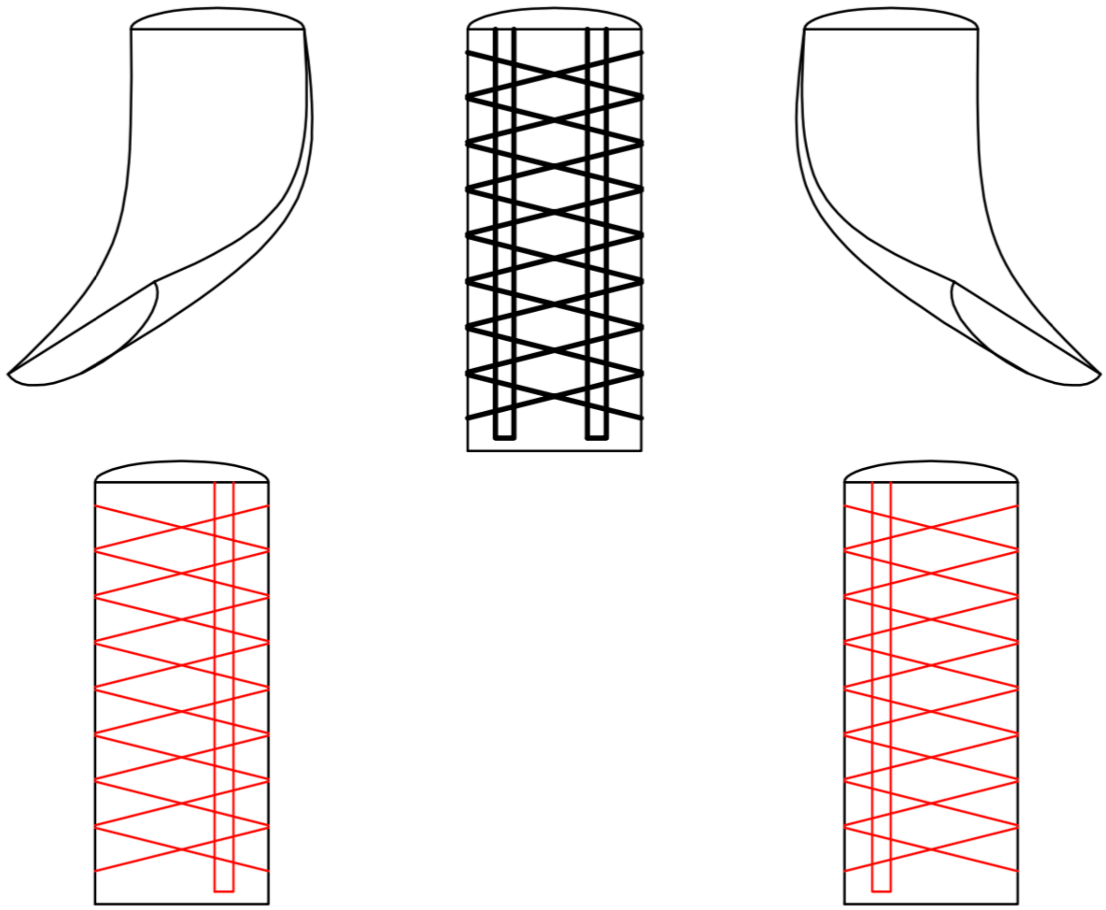


Figure 44 Illustration of a bending fluidic actuator with actuators arranged to bend and twist the actuator in both directions by activating each set of axial nylon wires individually. The activated nylon is shown in red and the resulting bending configuration is shown above.

Figure 45 Shows a further embodiment of the flexible fluidic actuator for achieving planar motion. By combining three bending fluidic actuators in parallel, planar motion may be achieved by activating the actuators in conjunction. This allows for the individual pressurization of the fluidic channels and allows for selective bending in the x-y plane of the actuator, as well as motion in the z-direction perpendicular to the plane of the actuator.

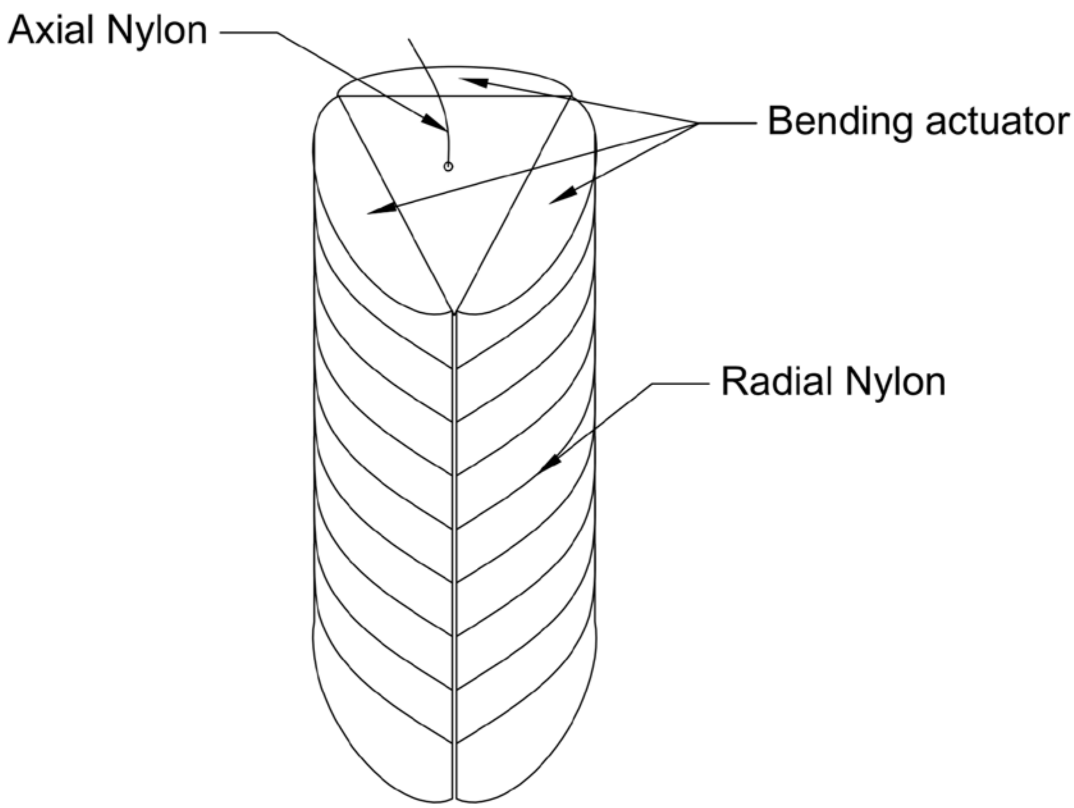


Figure 45 Illustration of a bending fluidic actuator with actuators arranged to allow for planar movement.

Figure 46 Illustrates a further embodiment of the flexible fluidic actuator for achieving planar motion. Three bending fluidic actuators, are combined in parallel similar to the configuration described in Figure 45. However, the actuators' cross section is designed such that the combination of the three forms a circular cross section.

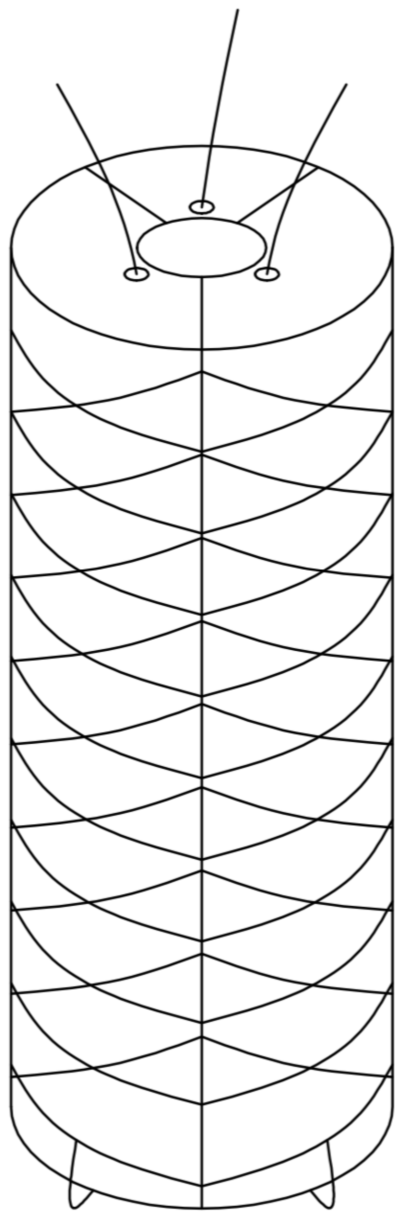


Figure 46 Illustration of a bending fluidic actuator with actuators 3 actuators arranged in a compact cylinder to allow for planar movement.

Figure 47 Illustrates a further embodiment of the flexible fluidic actuator for achieving planar motion. In this case, only a single cylindrical fluid bladder is required while three axial nylon wires are arranged in parallel to control the direction of bending.

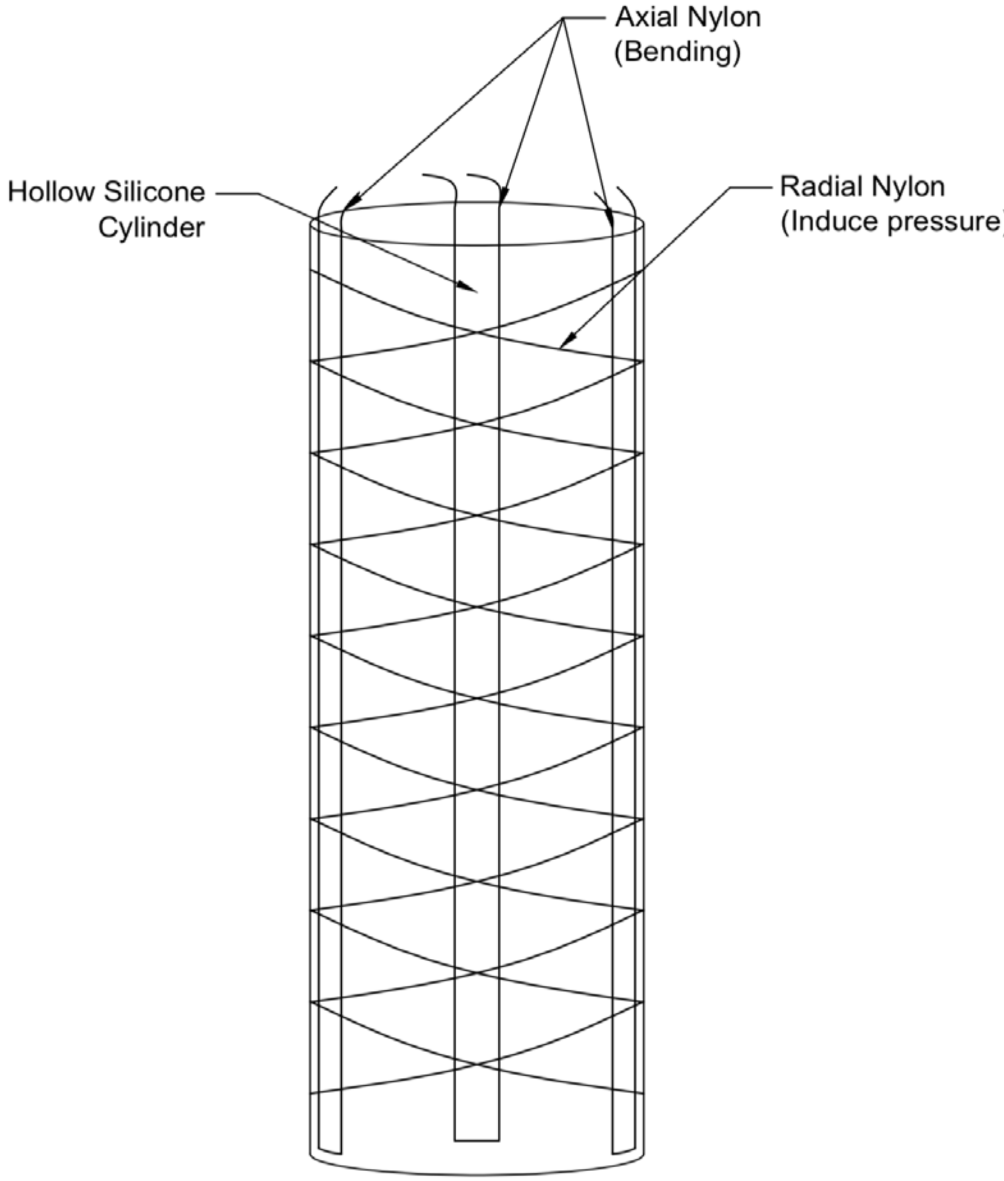


Figure 47 Illustration of a bending fluidic actuator with one fluidic actuator and 3 axial nylon wires arranged in parallel to allow for planar movement.

Figure 48 Illustrates a further embodiment of the flexible fluidic actuator for achieving planar motion. Two bending fluidic, are combined in parallel similar to the configuration described in Figure 46. However, the actuators' cross section is designed such that bending is increased in one direction. The proposed actuator may be useful for grasping and manipulating objects as it can bend in the direction of the object and twist after the object has been grasped.

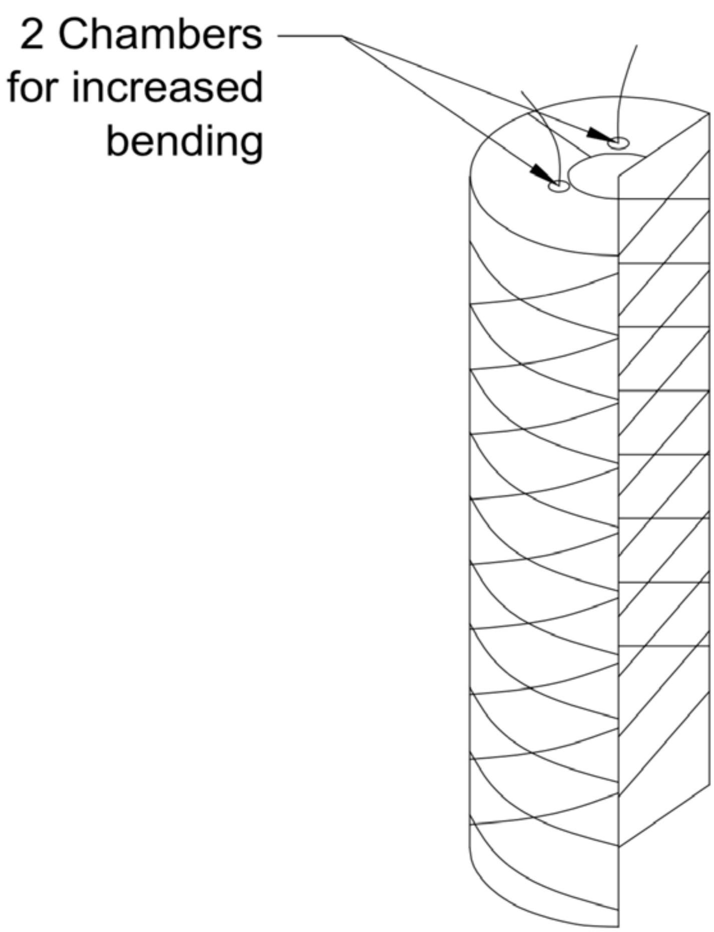


Figure 48 Illustration of a bending fluidic actuator with actuators 2 actuators arranged in a compact cylinder to allow for planar movement.

Chapter 9. Conclusion

The purpose of this thesis was to address the following objectives:

1. Explore the feasibility of developing a soft bending fluidic actuator which makes use of nylon artificial muscles eliminating the need for an external compressor or pump
2. Utilize established hyper elastic models to investigate the quasi-static behaviour of the proposed fluidic actuator
3. Verify the proposed model
4. Characterize the performance of the proposed fluidic actuator

The previous chapters address the thesis objectives as follows.

Chapter 3 focuses on objective 1; Explore the feasibility of developing a soft bending fluidic actuator which makes use of nylon artificial muscles eliminating the need for an external compressor or pump. By utilizing nylon actuators, the proposed fluidic actuator has no need for an external compressor or pump while still providing the benefits of a soft, compliant fluid actuator.

Chapter 4 focuses on objective 2; Utilize established hyper elastic models to investigate the quasi-static behaviour of the proposed fluidic actuator. The thermo-mechanical model for silver coated nylon actuators was characterized in previous research [17] [133]. This model was used to calculate the squeezing capacity of the nylon actuators. The actuator bodies were fabricated using Silicone TC-5005 from BJB Enterprises, which exhibits non-linear behavior during large mechanical deformations. Previous studies have shown that an incompressible Ogden model can accurately predict the deformation behavior of Silicone TC-5005 [20]. Combining the Ogden model for silicone with the force and displacement model for nylon actuators, a quasi-static model was developed for the proposed fluidic actuator.

Chapter 5 focuses on objective 3; verify the proposed model and partially addresses objective 4; characterize the performance of the proposed fluidic actuator. The position model showed a close correlation with the experimental data. A maximum displacement error of 4.2% was calculated demonstrating the accuracy of the models. The small discrepancies were likely due to the initial bending of the actuator caused by gravitational influences. Additionally, the force model showed good correlation with the experimental results (maximum force error of 4.3%). Using the analytical models, a minimalist position controller was implemented to demonstrate how a designer might implement a control system in practice.

Chapter 5 addresses objective 4; Characterize the performance of the proposed fluidic actuator. The analytical models were used to calculate a set of design considerations for the robotics engineer. The design plots outline the range of dimensions, and force requirements where the proposed actuator is most suitable. Furthermore, the design plots can be used select the optimal nylon fibre and actuator dimensions to best suit the designer’s requirements. Typically, the designer will select an actuator based on either the force requirements or the size constraints. For example, the designer can calculate the maximum forces achievable given a set of actuator dimensions. Alternatively, they can calculate the forces achievable given a set of actuator dimensions. Additional optimizations can also be made based on the nylon selected nylon coil index.

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