Design and Fabrication of Fabric Reinforced Textile Actuators for

Soft Robotic Graspers

by

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ABSTRACT

Wearable assistive devices have been greatly improved thanks to advancements made in soft robotics, even creation soft extra arms for paralyzed patients. Grasping remains an active area of research of soft extra limbs. Soft robotics allow the creation of grippers that due to their inherit compliance making them lightweight, safer for human interactions, more robust in unknown environments and simpler to control than their rigid counterparts. A current problem in soft robotics is the lack of seamless integration of soft grippers into wearable devices, which is in part due to the use of elastomeric materials used for the creation of most of these grippers. This work introduces fabric-reinforced textile actuators (FRTA). The selection of materials, design logic of the fabric reinforcement layer and fabrication method are discussed. The relationship between the fabric reinforcement characteristics and the actuator deformation is studied and experimentally verified. The FRTA are made of a combination of a hyper-elastic fabric material with a stiffer fabric reinforcement on top. In this thesis, the design, fabrication, and evaluation of FRTAs are explored. It is shown that by varying the geometry of the reinforcement layer, a variety of motion can be achieve such as axial extension, radial expansion, bending, and twisting along its central axis. Multi-segmented actuators can be created by tailoring different sections of fabric-reinforcements together in order to generate a combination of motions to perform specific tasks. The applicability of this actuators for soft grippers is demonstrated by designing and providing preliminary evaluation of an anthropomorphic soft robotic hand capable of grasping daily living objects of various size and shapes.

ACKNOWLEDGEMENTS

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1. INTRODUCTION:

1.1.   Motivation:

The aging population of the U.S.A is rapidly increasing, with estimates predicting the population over the age 65 reaching 20% by 2030. It has been observed that an increase in age is one of the main risk factors for a wide family of diseases that affect patient's mobility like, strokes and musculoskeletal diseases [1]. Stroke, as defined by the world health organization, is a clinical syndrome with rapidly developing clinical signs of focal or global disturbance of cerebral function, lasting more than 24 hours or leading to death with no apparent cause other than of vascular origin [1]. In America stroke represents the fifth leading cause of death. Even so the rate of deaths for stroke have been steadily declining in recent times thanks to improvements identifying and treating them. The current death rate of stroke patients is approximately 17.50%; however, stroke survivors are often left with some kind of impairment that will require intensive therapy for them to recover. The statistics show that 40% of survivors will experience major impairment requiring them to receive special care. The location and size of the stroke will play a crucial role in the impairment level patients. For example, if a stroke happens in the motor or premotor cortex section of the brain it will result in movement impairment. Some of the most common afflictions that the patients experience after stroke is paralysis or lose of function on one side of the body, hemiparalysis. Musculoskeletal disorders (MSD) are injuries in joints, ligaments, muscles nerves, tendons and other structures that help the human body support itself. Examples of MSDs that affect the upper limb are, trapezius myalgia, rotator cuff tendonitis, Lateral Epicondylitis, DeQuervain's Disease and carpal tunnel syndrome.

The cause of MSDs can be due to the accumulated damage of repeating a movement multiple times or performing a motion in an awkward posture. MSDs due to work related event represent 33% of all work-related injuries. The work-related aspect of MSDs makes it hard to treat this problem at its root as some of the activities that lead to this condition are also essential for job performance. The common thread in these two disorders is that both can lead to upper limb dysfunction. The loss of function of the upper limb is especially debilitating for patients due to the lost in autonomy they experience, being unable to realize complex manipulation tasks is greatly diminished. This also limits the individual's ability to participate in the workforce and reduces his or her quality of life. The common consensus amongst therapist is that most patients do not get nearly enough training during their sessions to achieve significant improvement [2]. Rehabilitation after a stroke is possible, however its costly and intense nature makes it difficult for most patients to achieve an appreciable level of progress [2] and often the pain felt by individual suffering of MSDs limits the work they can perform, in some cases driving them out of the industry they are qualified, impacting both their economic wellbeing and feel of worthiness. Solutions to address this problem have been proposed by multiple fields, from making ergonomics components that better fit the human body to therapy sessions to try to rehabilitate the affected limb. The advent of wearable assistive devices (WAD) has brought new life to previously established paradigms in regard to movement rehabilitation.

The explosion in popularity of WAD is in part thanks to advancements made in the emerging field of sort robotics. Soft robots make use of compliant materials, sometimes using materials with properties closely resembling biological tissues to create mechanically programmable actuators to carry out tasks. The reason that this technology has been so

popular in WAD, is that they address many of the issues stopping traditional robotics from being widely implemented in rehabilitation: safe robot human interactions, general lightweight and adaptability to new conditions. The study and design of artificial grippers have remained an active area of research in the field of WAD. As previously established, there are many conditions that reduce the function of the upper limb. The hand is one of the main appendages that humans use to interact with the environment, therefore the loss of any function on it can greatly impair the ability of a person for self-care and other activities of daily living (ADL). The remainder of the chapter will focus on discussing the basic ideas behind soft robotics, grasping, briefly go over the current state of the art grippers and the functional requirements of a soft gripper for assistive devices.

1.2.   Research Objectives

The main objective of this thesis is to design and develop fabric-based actuators capable of achieving varying motions by changing the reinforcements layer, similar to how Fiber Reinforced Actuators work. A preliminary anthropomorphic soft robotic hand was created as a proof of concept to show the applicability of the actuators.

1.3.   Grippers

Artificial grippers have fascinated researchers for centuries. The earliest known example of a semi-articulated artificial hand was the one used by the Götz von Berlichinge [3] , or Götz of the iron hand, a Frankish knight and mercenary from sixteenth century that lost his arm below the elbow due to cannon fire. His iron fist weighted approximately 1.5 kg and he was able to achieve a minimal level of dexterity by using a button to bend and release the fingers. Another curious example is the flutist robot created for the exhibit of J. Vaucanson [4] in the eighteenth century, it was a saloon robot meant for entertainment that played the

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flute by leather holstered fingers to play the flute. Since then the technologies of grippers have improved astronomically, with current technologies allowing the creation of grippers that closely match the human hand physiology.

For many years the main objective of artificial grippers was simply to imitate the human hand. However, in 1961 the first robot with a fully functional gripper, the UNIMATE, was deployed in a General Motors assembly plant. Since then the industry has heavily relied on grippers to perform task that either exceed human limitations or are too dangerous for humans. Thanks to this a new industry was born, focusing on developing grippers for the controlled environments of factories. The tasks performed by current state of the art grippers range from deep ocean exploration [5] to surgical robots able to perform complex tasks such as knee surgery [6]. The current trend in robotics appears to be focused on not imitating the human hand but finding the optimal architecture for a universal gripper. The reason that anthropomorphic hands have been so prevalent in research is that aside from cephalopods, they are known to be the most dexterous hands we know of.

1.4.   Mechanics behind grasp.

As it has been shown one of the goals of automation in general is to create robots that outperform humans in whatever tasks that they are given. One of the most challenging areas is grasping. The goal of grasping, in broad terms, is to achieve a desired object constraint in the presence of external disturbances [7].

For humans, the act of reaching out and grabbing something is a not an issue; however, trying to give this capability to a machine has been a headache for research groups for many years. Nevertheless, multiple models have been made that provide researchers with a good

idea of how grasping works. Analytical methods attempt to define the behavior between the gripper and the object mathematically.

The most common models used to explain artificial grasping in traditional robotics rely on the Hand Jacobean and the Grasp Matrix. The Hand Jacobean defines the force transmission properties of the contacts, while the Grasp Matrix defines the relevant velocity kinematics at the contacts. Theses matrices are used to determine the kinematics of the object for a unique grasp configuration as well as determining the behavior interaction of the object for this grasp [7].

Grasping with soft hands is quite different than grasping with rigid components, and this is because the assumptions made in the traditional model are not carried over. For traditional manipulation suitable points on the object are searched to obtain an optimal grasp while avoiding the environment. In contrast the soft hand conforms to the shape of the object allowing a greater contact area between the hand and the grasped object. Another benefit of soft hand is that it inherits compliance allows it to explore unknown environment and use it to gather further information that can be used to create a more robust grasp. However due to its compliance, traditional kinematic methods will not be enough to capture the behavior of the fingers' actuation. It is necessary to use continuum mechanics to accurately approach the behavior of more compliant continuous fingers.

The following sections will discuss current state of the art grippers both in traditional and soft robotics. The end of this chapter will summarize the parameters required to create the actuators for a soft gripper.

1.5. Traditional Robotics

It is important to note that robotic end effectors can be classified into two broad categories depending on their design principles, they can either be for industry (grippers) or human centered. Grippers are focused on being precise, fast and strong. Some of the best manipulators currently in the market are the:
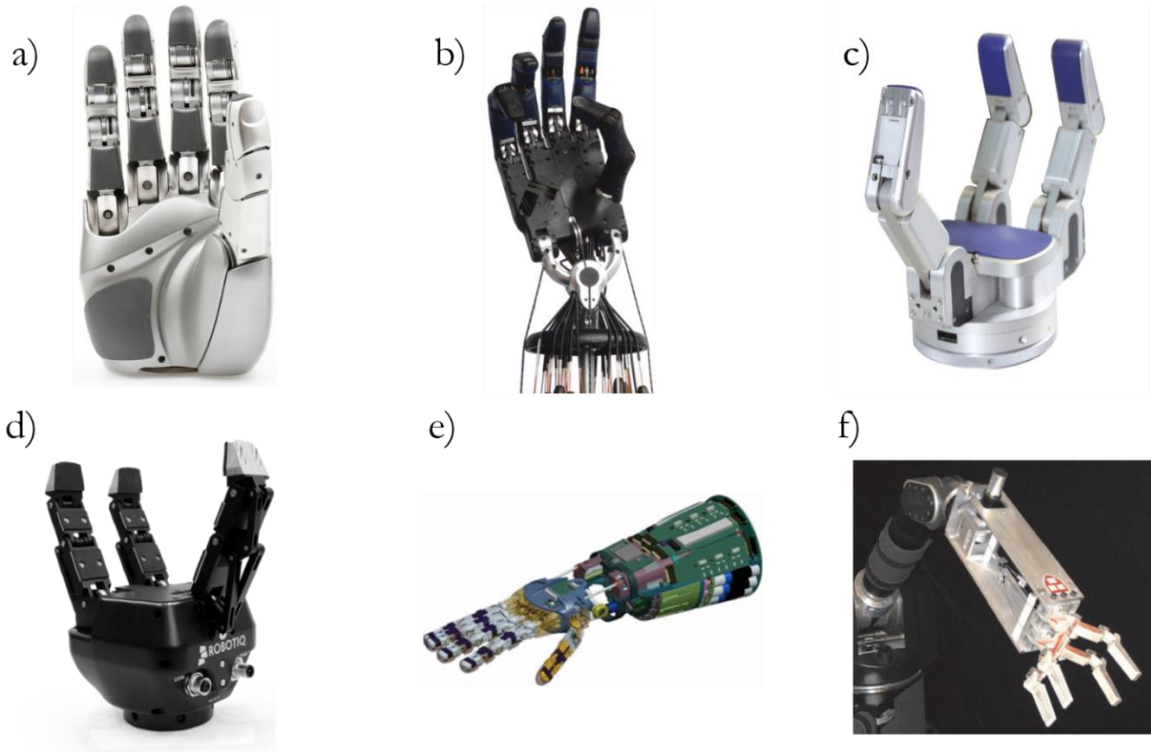
Figure 1 Traditional Robotics : a) DLR Hand [8] b)Shadow Hand [9] c) BH8-series Barrett Hand [10] d) Robotiq 3-finger gripper [11] e) Robonaut Hand [12] f) SDM Hand [13].

i. DLR Hand.

The DLR hand, Figure 1a, was designed with the goal of maximum flexibility and performance, the team decided to integrate all the components of the hand and reduce the cabling. It has 13 degrees of freedom (DOF) and can generated 30 N at the fingertips. [8] This was one of the earliest postmodern successful attempts to replicate the shape and anatomy of the human hand.

ii.   Shadow Hand

The Shadow Hand, Figure 1b, is a fully actuated artificial hand with force, position sensors and 20 DOF. It has 129 embedded sensors monitoring the position of the hand at all times [9]. It can achieve an open and close action in just 500 ms thanks to its high bandwidth interface. The Shadow Hand can use pneumatic air muscles (McKibben Actuators) or small electro servos.

iii.   BH8-series BarrettHand

The Barrett Hand, Figure 1c, is an intelligent, highly flexible eight-axis gripper that can reconfigure itself in real time to conform to wide variety of part grasps [14]. It was designed and developed by Barrett Technology with the goal of creating a dexterous, standard architecture for the industry. It has a payload of 6.0 kg weights 980 g, uses 4 hand motors to control its three fingers. The BarrettHand is interesting because its design allows for free rotation of two of its fingers around its palm, allowing it to perform more complex manipulation tasks such as using a drill to make a hole and change a light-bulb. [10]

iv.   Robotiq 3-finger gripper

The Robotiq 3-finger gripper, Figure 1d, is the next iteration of the SARAH hand designed in 1999 by Laval University. The whole hand weights 2.3 kg, can grasp objects anywhere from 20 mm to 150 mm, lift up to 10 kg and generate a fingertip force of up to 70 N [11].It has been shown to be able to handle everyday objects such as chairs, fruits, vegetables and soda cans with adequate dexterity. The gripper has also been used as the primary manipulator for multiple finalist designs in the DARPA Robotics Challenge and has been used extensively in research due to the ease of integration into existing robot arms[11] .

v.   Robonaut Hand

The Robonaut hand, Figure 1e, is a conjoint effort between N.A.S.A and General Motors to create an artificial gripper for extra-vehicular activity (EVA). The first iteration was published in 1999 and was a five-finger anthropomorphic hand with integrated wrist and forearm. It had 14 DOF. The second generation called Robonaut 2 Hand, according to its designers greatly improves over the original capabilities of its predecessor. The Robonaut 2 Hand is more dexterous, had greater force control, and sensing. It also has a more anthropomorphic design that allows it to perform different human grasps. It is capable of generating 22 N of force while extended, achieving a maximum payload of 9 kg and its fingertips achieve a velocity of 200 mm/s [12].

<div align="center">vi.   SDM Hand.</div>

The Shape Deposition Manufacturing (SDM) Hand named after its construction method. Figure 1f, was designed by Harvard, as a highly compliant hand for unstructured grasping [13]. The fingers of the hand are tendon driven, using a low friction stainless steel cable. The pulley design enables the hand to achieve full contact grasp by allowing the fingers to close into the object even after the other fingers have reach it, also allowing it to passively adapt to the shape of the object being grasped. In total the hand has 8 DOF being actuated by a single actuator. The authors do not call it a soft robot min the original paper, but this hand has all the marks of a soft robot. The focus of the authors wasn't necessarily force but instead precision and dexterous manipulation. In the paper the SDM hand is showing to successfully achieve a wide array of grasp on everyday objects such as a full glass of wine, a CD and a drill.

1.6. Soft Robotics

The following section will discuss the emerging technologies that have come out of the field of soft robotics to address the problem of grasping. Rather than discussing each example individually this section will introduce the methods of actuation for each gripper and then proceed to discuss prominent examples of each one.

i. Cable Driven

One of the most popular actuation methods of actuation for artificial grippers is to use cables attached to servos or pneumatic artificial muscles to pull on the structure that can be thought of as the finger. A state-of-the-art example of this would be the soft hand developed by the collaboration of the university of Pisa and the Istituto Italiano di Tecnologia. The Pisa/IIT hand is a tendon driven artificial gripper designed by the PISA institute in Italy. [15] It controls 19 DOF using a single electrical motor. It was designed with the goal of utilizing muscle synergies, a phenomenon though to be implemented be the human brain to dexterous manipulate the objects [16]. The suggested idea by synergies is that the brain controls the human hand not as a collection of independent articulations of muscles. The result is an amazingly simple design that still achieves robust grasps. This design can be considered to be a standard of quality of what can be achieved by underactuated hands. The force generated by the Pisa Hand was observed to be determined not by the hand architecture itself but by the size of the motor used, with the reported maximum being 20 N. The two main grasps achieved by the hand are power grasp or tip grasp. Another interesting aspect of the Pisa Hand is the human operator interface designed for it, opening the potential to for it to be used as a wearable or prosthetic system. In fact, this potential was explored in the SoftHand Pro (SHP), a myoelectric controlled prosthetic.

The SHP is heavily inspired by the design of the Pisa/IIT hand, implementing the same concept of synergies. The SHP weights 520 g is 200 mm from the tip of the middle finger to its tip, and the palm is 90 mm wide. It can provide 76 N for power grasp with 20 N in pinch grasp and can pick up objects exerting up to 400 N. [17]. Both of these hands present impressive results and their actuation method definitely fall in line with the new methods being developed by other tendon based soft hands. However, both of these hands still use rigid components as the main method force transmission. Even so using even softer materials to

Another impressive examples of cable use to replicate the human hand is work off

The Biomimetic Anthropomorphic Robotic Hand developed by the University of Washington is an impressive recreation of the human hand. The goal of the research group is to imitate not only the anatomy of the human hand but also its physiology. The team was so dedicated to recreating the human hand that they scanned, and 3D printed the all the bones of the human hand. To recreate the tendon, they laser cut two layers of elastic material in the shape of "hoods" and then anchored the ligament to anatomically similar positions in their 3D printed bones. The hand uses ten servomotors to pull on these tendons to achieve grasping[18]. In their paper they show it to have great success in performing most human grasp taxonomies as established by M.R. Cutkosky. by teleoperation.

ii. Pneunets.

Pneunets were one of the earliest soft actuators developed by the Whitesides Research Group of Harvard. Pneunets stands for embedded pneumatic networks, at their more basic level consist of an elastomeric structure with a hollow chamber, that actuates via pressurized fluid. The nature of the motion heavily dependent on the shape distribution material properties of the walls of the embedded network [19]. The research group that developed these networks

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used them to create a starfish-like gripper as a proof of concept to show the applicability of this actuator. Aside from a gripper the Pneunets have also been used to create assistive gloves for stroke patients [20] and slow locomotion robots [21], The main advantages of this kind of soft actuators is that by combining materials with different stiffness or by slightly changing the shape of the network complex motions can be achieved from a single input. Many of the most recent soft actuators use the design principles of the Pneunets as a basis to achieve motion.

iii. Fiber Reinforced Actuators

Fiber reinforce actuators are elastomer structures encased in a reinforcement to control its deformation. The elastomeric chamber when pressurized will expand in all directions, the fiber reinforcement will constraint the expansion of the elastomer. The direction of the motion as well as the expansion of the actuator will depend on the fiber orientation and placement. It has been shown that by ingenious placement of the fibers a combination of bending, twisting and twisting can be achieved by a single actuator. [22] The advantages that FRAs offer over Pneunets is that FRAs have a wider array of motions and also exhibit a higher sturdiness. *Galloway et al, 2015* developed a gripper meant for underwater exploration using FRAs. The gripper was designed to imitate the motion of a boa or cephalopod around the grasped object. It was observed that the maximum pulling force of the actuator was close to 56.8 N and was able to grasp objects as small as 12 mm. The FRAs developed by the team were successful in retrieving multiple samples of coral in their pilot study.

An anthropomorphic hand using FRAs was developed by Zhou et al 2018, called the BCL-13 is 13 DOF underactuated hand. It consisted of three purely bending fingers and a thumb that could achieve bending and rotation thanks to being attached to an extra actuator

at the base of the palm. The hand was capable of achieving three modes of in-hand object manipulation: translation, rotation and reorientation [23].

Another type of actuator that use the same concept as FRAs, with some modifications is the Pneuflex developed by Deimiel and Brook. The Pneuflex actuators were designed with the overall goal of being used as fingers for an artificial gripper, therefore the shape and constraints were optimized for bending [24]. The main difference being that it is easier to vary the cross-sectional area of Pneuflex actuators when compared to FRAs. Pneuflex actuators have been integrated into state-of-the-art soft grippers called the RBO Hand I/II. The RBO Hand is capable of achieving 31 out of the 33 grasp postures from human taxonomy, weight only 178 g and can carry a payload of 500 g [25].

iv. Knit Testing Bending Actuator (KNTB)

Capello et al. developed fabric-based pneumatic actuator (FBP) that uses the anisotropy between different kinds of fabric to achieve complex motions. The overall concept of intelligently constraining the stretch of elastic materials remains the same. The inner chamber of the KNTB is a simple balloon made of some elastomeric material (TPU) that is constrained by a stretchy textile. The key goal here is to use the inner chamber to expand the fabric in the desired direction. As they demonstrated in the soft robotic tool kit by combining different kinds of fabric, they are able achieve complex motions such as bending, extension and twisting is by using stretchable fabric with different strains (the wale and course direction). The application of this kind of actuator have been shown in a soft rehabilitation glove [26]. The main advantages that this kind of fabric-based actuator offers over elastomeric actuators are its lightweight, low operational pressure and greater compliance. The FBO can reach a

contact force of 15 N at 172.4 kPA and was theorized to be able to hold a weight of 750 g. These characteristics make it an attractive solution to create wearable or assistive devices.

Another group that has exploited the anisotropic nature of textiles was Connolly et al 2019, their focus aside from showing the characterization of actuators entirely made of stretchable textiles was to create a sew free actuator without the internal to increase fabrication repeatability. They showed that by lamination of the same textile used in *Capello et al 2017* it was possible to create a similar bending actuator without the need of sewing the material together. Due to the fact that many times when creating textile base soft actuators, the quality of the stich and the personal skill of the manufacturer come into play, creating a method that completely removes the need for sewing the actuator greatly reduces the time spent creating the actuator and variability of its performance. Aside from creating sew free method for textile actuators Connolly et al also showed how the actuators they created could be further reinforced with rigid film to constraint the radial expansion of the fabric, adding the possibility of further programming actuator motion. The fabric actuator developed were 110 mm long and 10 mm wide, being able to curl up to the 1.5 °/mm [27]. They similarly showed the applicability of this kind of actuator by creating an assistive glove for stroke patients.

v.   Continuum Octopus grippers.

The movements of the OctopusGripper, designed by Festo, are designed to behave much like the tentacles of a cephalopod, it has 12 DOF and can carry up to 3 kg. The robotic arm is made up of three segments, composed of four pneumatic bellows covered in 3D textile knitted fabric. The gripper is pneumatically controlled. Once inflated the gripper can wrap compliantly around any item. The modular design of the OctopusGripper make an attractive design for researches. [28]

The robotic arm developed by Cianchetti et al, was also heavily inspired the anatomy of cephalopods, specifically their muscular hydrostats.[29] The arm was able to elongate up to

Another example of a continuous gripper is the fabric-based continuous gripper developed by the by the Bio-Inspired Mechatronics Lab. This gripper is made up of multiple small bladders sew into an inextensible layer of fabric [30]. The bio-inspired continuum gripper shows that by selectively inflating the bladders different curling states can be achieved by it. This gripper is also able to be compressed up to 3.6 times its original size due to the highly compliant fabric used create it. The gripper had a payload of at least 51.5 N payload during pullout testing. This gripper also makes use of a pneumatic wrist, having a ROM from 0 to 118.3 ° and output torque of 2.79 Nm.[30]

vi. Granular Jamming

Using the fact that granules become hard when in a vacuum and soft with air, many groups have been able to develop what is essentially a universal gripper. This mechanism is called granular jamming, the depressurization of a loose granule filled bag produces compressive forces between the granules, which constrain their physical movements, making the whole bag behave as one solid object. The change of stiffness achieved by granular jamming has been recorded to be 24 times originally stiffness [31]. The main advantages of this kind of grippers is that it is easy to achieve high speed and torques, as well as precise movements if the environment can be considered stable. Another major advantage that remains an important issue with soft robotics is the issue of force transmission. Rigid designs due to the materials properties do not have to worry too much about effectively transmitting from the motors via the links to the object. The disadvantages of this design are that for stable grip the system needs constant feedback, it is hard to achieve dexterous manipulation of the

object under unknown conditions, even with constant feedback the perception required to make the small changes to adjust the grip is computationally expensive for rigid designs. A two fingered configuration, developed by Amend and Lipson, is dexterous enough to handle chopsticks to manipulate small objects. Li et al integrated a jamming section into a FEAs, in here the bending squeezes the jamming part confining the granules inside without the need of a vacuum.

vii. Modular Soft Robotic Gripper

The Modular Soft Robotic Gripper Developed by MIT is a three fingered pneumatic gripper designed to be mounted on the wrist a Baxter robot. This is one of the first examples of integrating soft robotics and traditional robots. The design used for the soft fingers used the same anisotropy strain concept previously exploited by Pneunets and Pneuflex. The gripper is also capable of identifying objects based on data from internal flex sensors. K-means were used to distinguish objects being grasped [32]. The data from the sensors was essentially used to calculate the position of the fingers as they enclosed the object and then from this calculation the closest match to the current position was used to classify the object. This along with its modularity to be used with preexisting robotics arms have shown the potential of soft robotics to be integrated into the industry.

viii. Electroactive Polymers/Shaper memory Alloy grippers

As advancements in material sciences have increased during the recent years new interesting materials have been made available to use as actuators. Amongst these materials two in particular have been quite popular for the development of robotic grippers, they are EAPs and SMA.

The main attraction points of these materials are their potential to be miniaturized, low-mass, low power and ability to contract on command under electrical excitation. Dielectric Elastomer Actuators consists in a thin elastomer membrane sandwiched between two compliant electrodes, by running high voltage by the electrodes, electrostatic attraction between them squeeze the elastomer in between. The use of DEA has seen increased interest in the soft robotic community due to the material similarities to human skin. The main disadvantage is that the force produced by the DEAs is low, requiring stacking of multiple layers to achieve the forces generated by other soft actuation methods.

Ionic Polymer-Metal Composites consist of an electrolyte swollen polymer membrane sandwiched between two thin metallic layers. With no voltage applied, the anions and cations in the electrolyte in the polymer are uniformly distributed. When a voltage bias is applied to the electrodes, the cations migrate toward the cathode, and the anions toward the anode. This leads to differential swelling, causing a bending deformation of the entire structure toward the positive side. The main disadvantages of IPM are that it is quite slow, it builds up hysteresis, and it needs to be encapsulated in an aqueous solution to be used effectively and it produces low stresses.

1.7.   Functional Requirements

The functional requirements for artificial grippers will vary depending on the kind of environment the gripper is intended to be used on. Usually artificial grippers can be divided into human centered or industry centered gripers. Human centered grippers have a focus on dexterity, quickness, durable, adapting to unknown environments. Industry centered gripers place a heavier emphasis on reliability, task repeatability, force. For the purposes of this thesis the focus was to develop an artificial gripper to be used as an assistive device for ADLs the

focus was placed on what would make and ideal gripper for daily life use. To determine the functional parameters necessary a literature review was performed the results are shown in Table 1.

Table 1 Functional Requirements of a soft gripper

Functional Requirements	Rationale
Weight (g)	This griper will be incorporated to soft arm, can't increase the weight too much
Grasp Size (cc)	Must be able to grip Daily Life size objects
Operational Pressure (kPa)	Mustn't exceed what's available in commercial available pumps
Grip Force (N)	Will determine the stability of the grasp
Payload (Kg)	The maximum weight that the gripper can handle
# of fingers	An increased number of finger will increase stability but also increase complexity
Power	Lower power consumption will prolong the battery life
Actuator Length (cm)	Will determine the effective grasping volume and robustness of the actuator.
Reaction time (s)	Will need a small value to make the device usable
Dry Friction	Will determine how stable the grasp around the object

It was decided to go with an anthropomorphic design as most grasp types test and also objects in daily life have already been optimized for human hands. Another reason this design was chosen was because it was concluded that this design would facilitate human-robot cooperation of the gripper.

2. FABRIC-REINFORCED TEXTILES ACTUATORS

2.1. Actuation Principle

The principle of actuation for the FRTAs follows the main idea behind elastomeric FRAs, using the programable differential elongation of the material to generate motion; this kind of behavior is called anisotropy. Anisotropy can be achieved in multiple different ways, like using materials with varying strains at different layers [33], fiber reinforcements [34], hybrid structures [35] or sleeves [36]. Creative combination of strain limiting sections can be used to produce different deformations when pressurized. In all of these cases the ideal will be for the elastic material to stretch purely along the longitudinal direction, as any radial expansion reduces actuator performance, decreases durability and operational pressure.

Common materials for the creation of SPAs are elastomers of various strain that act as both the inflation and body of the actuator. There are many benefits offered by elastomeric SPAs; their strain curve is similar to that of biological tissue making them appealing to groups attempting to replicate biological systems. Their low elastic moduli make them easy to deform and gives them an inherit compliance. Elastomeric SPAs are also highly resilient being able to tolerate 100's kPa and still work properly [21]. Thanks to their prevalence in the soft robotic field, elastomeric soft actuators have been widely researched creating a plethora of knowledge, characterizing the deformation behavior of various architectures, gaining a solid understanding of their surface chemistry and also having developed a wide array of sensing techniques for it. For all the benefits that elastomeric polymers offer there are still some glaring issues that prevent their widespread use. Some of the issues with the current eSPAs are that even though polymers are more compliant than materials found in traditional robotics, their compliance is not absolute when deflated, making the actuators resist motion in the more rigid direction. In

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some cases, the reinforcements will damage the elastomer, or even reduce its movement. The most prevalent SPAs used in research at the moment is the fiber reinforce actuator (FRA), it uses an elastomer as the main body, covered in fiber reinforcement (usually Kevlar thread) to generate bending, different groups shown that by varying the orientation of the fibers the actuator can achieve motion such as extension, twisting and bending.

Another type of actuator that has been gaining momentum over recent years are textile-based actuators. Textile actuators consist generally in encasing a thermoplastic elastomer inner bladder in a fabric shell. The inner TPU bladder serves to hold the air pressure by which the actuator achieves its function. This TPU bladder is essentially just a balloon, but by using a fabric shell to program its deformation, multiple shapes and motions are achievable. The type of fabric used will determine the shape of the actuator when fully inflated. Using textiles to create SPAs open a whole realm of possibilities for their design and fabrication. The thin sheet like structure of textiles makes them lightweight and allows for the use of 2D manufacturing methods. Additionally, textiles are way more compliant than elastomers when deflated, making their storage and transportation simpler. When inflated their high compliance will have them conform to the shape of the object better than elastomers. The main drawbacks of textile base actuators are that they remain even more unexplored than other soft robotic technologies, the modeling of their dynamic and static behavior is hard and sensing technologies still have to catch up to this actuators.

In the following section the main parameters related to actuator behavior, how they affect its performance a simple mathematical model for determining the actuator behavior, the fabrication method, testing and evaluation of the actuator will be shown.

2.2. Material Selection

As with many other soft pneumatic actuators (SPAs), the materials used to create the main body of the actuator are crucial to the actuator performance. The main properties that were desired from the elastic fabric was for it to have a high directional stretch and have a high denier. A higher stretch in one direction allows the actuator to retain a semi-regular shape. Denier is a unit of measurement used to determine the fiber thickness of individual threads or filaments used in the creation of textiles and fabric, which will affect the thickness and durability of the fabric. A higher denier corresponds with an increased value in all parameters.
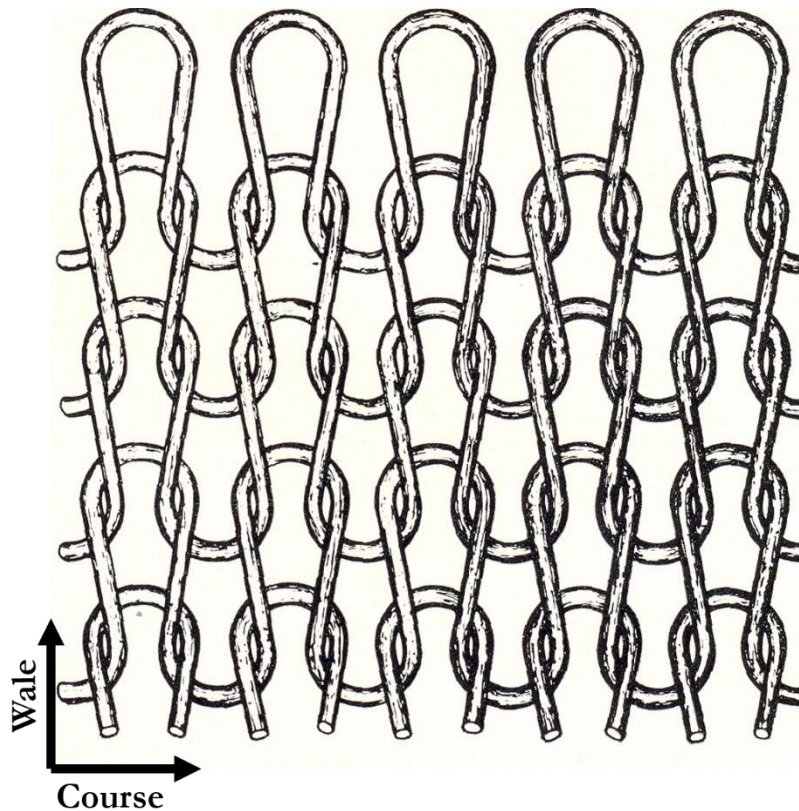
Figure 2 Knit textile

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2.2.1. Hyper-elastic material

To create programmable FRTAs it was important to have a material that during its natural state showed signs of behaving as desired. The main qualities desired for the material were for it to have directionality in its stretch, anisotropy, and also resilience, high denier.

The reason for making anisotropy a crucial property of the selection process is that the difference in stretch is used as the driving force to achieve motion. Therefore, a high level of stretch in only one direction was the key parameter that was observed for deciding what fabric to use. The mechanical properties of the high-stretch textiles were characterized by conducting uniaxial tension tests using a universal testing machine (UTM Instron 5944, Instron Corp., High Wycombe, United Kingdom) on both the uncoated knitted textile material and TPU coated/laminated knitted textile material. The high stretch knitted textile (24350, Darlington Fabrics, Westerly, RI) is composed of 83% 50 Denier Semi-Dull Nylon and 17% 210 Denier Spandex fibers. Using the ISO-139134-1 standard, these knitted materials were tested in both the wale and course directions. It is noticed that in the wale direction, parallel to the direction of manufacturing, the knit has a higher stretch of 426.8% at 72.41 MPa. In the course direction, perpendicular to the direction of manufacturing, the stretch was stiffer at 240.1% at 73.14 MPa. The TPU-laminated textile material showed an increase of an overall stiffness in both directions but still preserves of the mechanical anisotropic properties of the knitted textile material at 422.9% at 83.78 MPa (in the wale direction) and 240.1% at 71.01MPa (in the course direction).
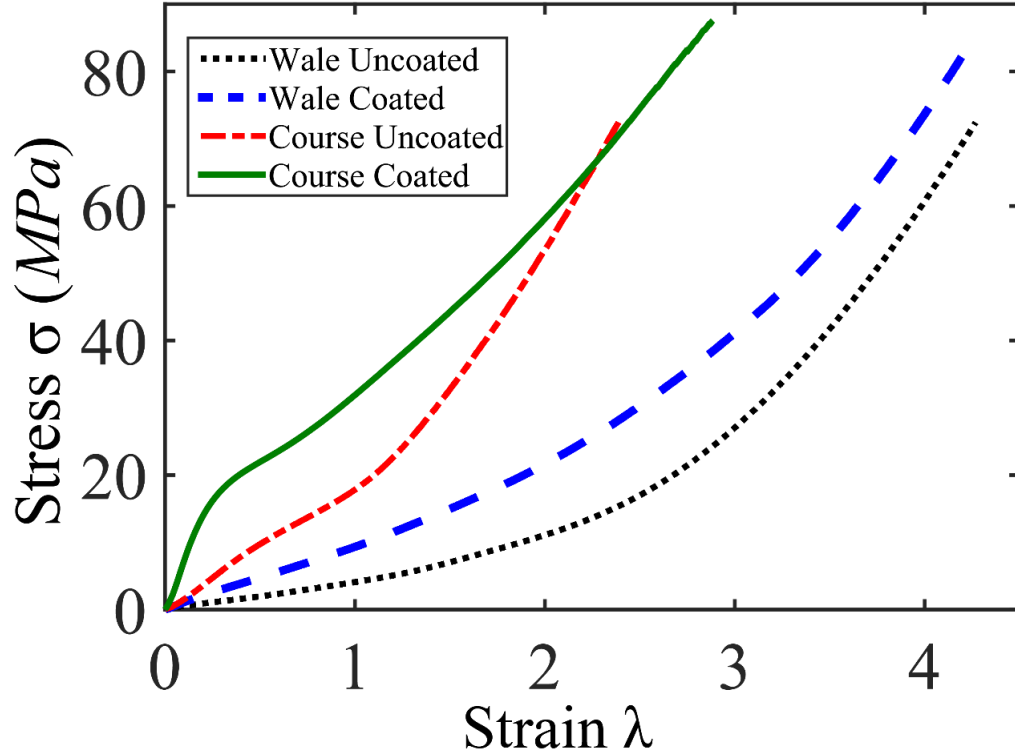
Figure 3 Experimental stress-strain of the high stretch textile

2.2.2. Reinforcement material

Another material choice that will impact the behavior and quality of the actuator is material of the fabric reinforcement. The key aspect of the fabric reinforcements is that while they constrain radial stretch, they still allow axial stretching of the material. The main material parameter to keep an eye on is the denier of the fabric. As the process of creating the actuator requires lamination it is also important to choose materials that will work well with this process. Therefore, materials with a high denier were selected to create the reinforcement layer of the actuators. However, one has to be mindful of how high on the denier of the fabric as the higher the value the less complaint the material will be. This will not only reduce the compliance of the actuator itself but also complicate the fabrication process. For the project

three different types of reinforcements layers were tested with deniers 100, 400 and 1000 D. The Young's moduli were determined by using ASTM D882, the values ranged from 498, 635 and 222 MPa.

2.3. Mechanical Programmability

FRTAs use a combination of highly stretchable and inextensible fabrics to control their deformation in order to generate motion. The high-stretch fabric shell acts as the main driving force of the actuator while the inextensible fabric helps control its deformation.

The actuator itself could be considered as being composed of three layers: the inner TPU bladder, the high stretch textile shell and the inextensible fabric reinforcements. Therefore, the main parameters to consider when designing FRTAs are the maximum elastic strain of the high-stretch fabric both in its main and off direction, the strength of the fabric reinforcement fabric, the overall geometrical shape reinforcement cage and the location of any strain limiting section.

The main advantages of creating the actuator out of fabric are that the complexity of fabrication is greatly reduced when compared to elastomeric SPAs methods. All the materials required for the actuators are thin sheets which allows 2D manufacturing processes such as laser cutting, sewing and lamination. These processes take less time, waste less materials and reduce the variability in performance of actuators. This is in part thanks to the reduce number of steps needed for fabrication, as well as the fact that aside from choosing an appropriate elastic fabric, there's no need to prepare a mix like in elastomeric based SPAs.

Thanks to the mechanical programmability being housed solely in the reinforcement layer, it is easy to make changes to it to explore possible design to achieve a desired function.

For all the advantages that using textiles offer this method is not flawless and some of the benefits of using elastomers are not present.

First of all, the FRTA requires an inner plastic bladder to work, not only does this increase the level of variance, but also limits the tolerable pressure of the actuator (pretty sure the fabric gives up before the TPU). One also has to be careful during the lamination process as if the temperature is set too high or there's a lack of protective layer the fabric will not laminate properly or lose strength.

The designer should also be careful not to add a strain limiting section if purely extending or twisting actuators is desired. Lastly, as it will be shown in the evaluation section, the amount of reinforcements plays a critical role not only in performance but also in durability and operable pressure of the actuator. It suffices to say for now that a greater number of reinforcements will increase the all these parameters.

Designing the Reinforcement layer:

The main idea behind using a reinforcement layer comes from the Kevlar in FRAs. As it has been previously discussed and will be shown in the evaluation section radial expansion is something that for the purposes of FRTAs is considered a demerit. The reinforcement layer main purpose is to reduce the radial expansion of the actuator as it is inflated. This reduction in radial expansion not only improves actuator motion performance at the same pressures but also improves the durability and increase the tolerable pressure of the FRTA. There are two reasons not to use a solid piece of fabric: 1) this would create an inextensible reinforcement all across the actuator limiting the stretch of the high-stretch fabric to that of the inextensible layer and 2) the actuator will not able to achieve complex motions. This would not necessarily prevent the actuator from achieving motion but would increase the required pressure to levels

well beyond what portable pumps and valves are able to provide. The second reason for not using a full reinforcement cover is that the complicated behavior such as finger motion that inspired this work would not be possible as previously stated the direction (alpha) of the reinforcements can be used to create a combination of motions for the FRTAs. Therefore, it is of interest to the designer of the reinforcements to find the appropriate balance between the space, size and number of reinforcements needed to create the desired motion. A good rule of thumb is to allow at least 1 mm gaps in between reinforcements to constrain the radial expansion as much as possible

2.4. Fabrication

As previously stated, the fabrication processes use 2D manufacturing methods for the fabrication of FRTAS. The fabrication method for the actuator is designed to reduce both the amount of time and skill needed to construct the actuators. All actuators follow a similar fabrication process the main difference being between the purely bending actuators having a strain limiting segment at the fulcrum of the cylinder (bottom layer) and the purely bending/twisting having no strain limiting segment and being sealed at both sides. Figure 3 shows a summary of the steps required to create the FRTAs.
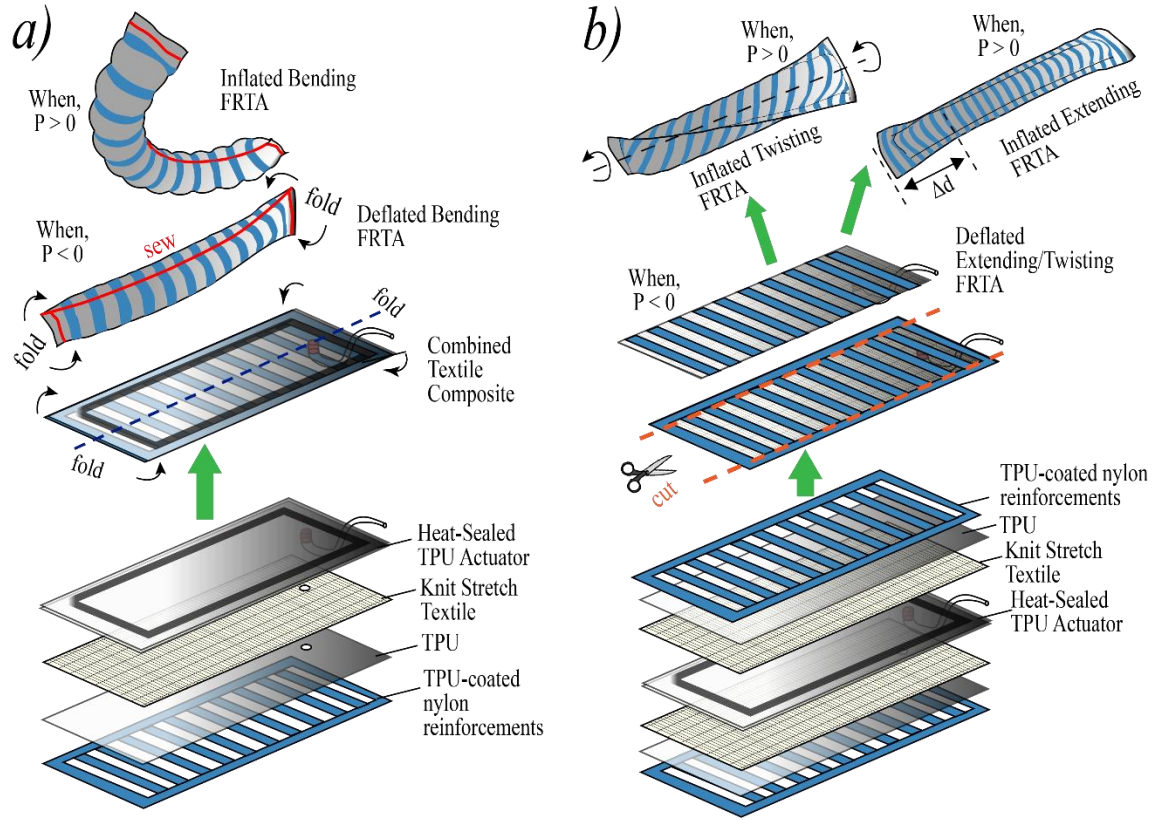
Figure 4 Fabrication of FRTAs: a) Fabrication of bending type FRTA b) Fabrication of extending/twisting FRTAs

2.4.1. Cutting

To fabricate the FRTAs, the high-stretch knitted textile (24350, Darlington Fabrics, Westerly, RI), TPU material (Fastelfilm 20093, Fastel Adhesive, Clemente, CA), and the TPU-coated nylon fabric (6607, Rockywoods Fabric, Loveland, CO), used as the fabric reinforcements, are cut into the desired shape using a laser-cutter (Glowforge Prof, Glowforge, Seattle, WA). A small hole (less than 1 mm) to attach the tubing at approximately 30 mm from the top of the actuator.

2.4.2. Lamination

To create the bending actuators, a thin TPU sheet is laminated over one side the knitted textile to create an adhesive side, using a heat press (FLHP 3802, FancierStudio, Hayward, CA). This side is used to bond with the sheet of TPU-coated nylon fabric reinforcements using the heat press the ideal temperature for this lamination process is 340 °F, this temperature melts the TPU into the fibers of the fabric. A TPU actuator, heat-sealed using a custom CNC router, with a modified soldering iron tip (at 320 °F) was used to create the bladders. The thread used to put the pieces of fabric together will also act as a strain limiter for it. This makes the choice of adequate thread important to determine the actuator behavior.

2.4.3. Placing Inner TPU bladders

The thicker TPU is heat sealed in all but one side using a CNC router with modified tip. The side left open will be used to connect the fabric encasing and the TPU bladder.

2.4.4. Sealing the Actuator

Before completing the actuator Pneumatic fittings (5463K361, McMaster-Carr, Elmhurst, IL) are used to connect the TPU bladder previously prepared. The combined textile composite, with the TPU actuator in between, is folded along the center and sewn to create a strain-limiting, inextensible centerline to allow bending. For twisting the edges of the combined textile composite are heat-sealed using an impulse sealer (751143, Metronic, Seattle, WA). The heat-sealed edges still allow the actuator to stretch along the axial axes, so that it can extend or twist.

3. TESTING AND EVALUATION OF ACTUATOR:

3.1 Actuator Characterization

To characterize how the interactions of the high-stretch fabric and inextensible fabric would change depending on the patterns of the reinforcement layer, different patterns were tested. Three hypotheses were tested that 1) the addition of a strain limiting section would make the actuator bend, 2) the orientation of the fabric reinforcements would change the direction in which the actuator moved, and 3) the radial expansion of the actuator would negatively impact the actuator performance regardless of its motion. To test these hypotheses three groups of actuators with different reinforcements patterns were tested. The trajectory of the actuator and its internal pressure were recorded by using a motion capture system and pressure sensors, respectively. Radial expansion was manually measured with a caliper at three different locations and then averaged.

$$\theta = arccos\left(\frac{(\hat{a}\cdot\hat{b})}{|a|*|b|}\right) \qquad (1)$$

$$D = \bar{x}_2 - \bar{x}_1 \qquad (2)$$

Equation (1) was used to calculate the bending and twisting angle, where a is the vector going from the base to the middle section of the actuator, and b is the vector going from the middle to the tip of the actuator. The extension equation (2) was used, x_1 is the marker at the base and x_2 is the marker at the tip.

3.2. Methods

All the actuator tested had the same length, 170mm, and width of 90mm. A motion capture system (Optitrack Prime 13W, NaturalPoint Inc., Corvallis, OR), a custom rig running LabView (2017) was used to control solenoid valves to increase the pressure of the actuator.

In all cases the actuator was inflated from 0 to its maximum pressure in intervals of 13.8 kPa every ten seconds allowing another ten seconds for the internal pressure to reach equilibrium.

3.2.1. Bending and Extending

For the bending actuators one marker was placed at the base, middle and tip of the actuator. For extension two makers were deemed sufficient to kept track of the actuator extension as only the length of the FRTAs was being recorded. For each motion three actuators were tested. The bending and extending actuator were tested with *n=6,12, and 24* and alpha=0. The main difference between the two was the addition of a strain limiting segment for the bending actuators. In addition, the bending motion of the reinforcements made of the fabric with denier of 400D and 1000D were tested in a similar fashion with *n=24*. The testing pressures were increased to 207 kPa, as it will discussed in the following section the increased strength of the reinforcements increases the bending angle and the operable pressure of the actuator.

3.2.2. Twisting

For twisting actuators, the pressure needed to achieve its maximum actuation state was lower at 110.316 kPa. The twisting actuators were tested. It is noted that the major radial expansion for bending actuators happened at the longitudinal center.
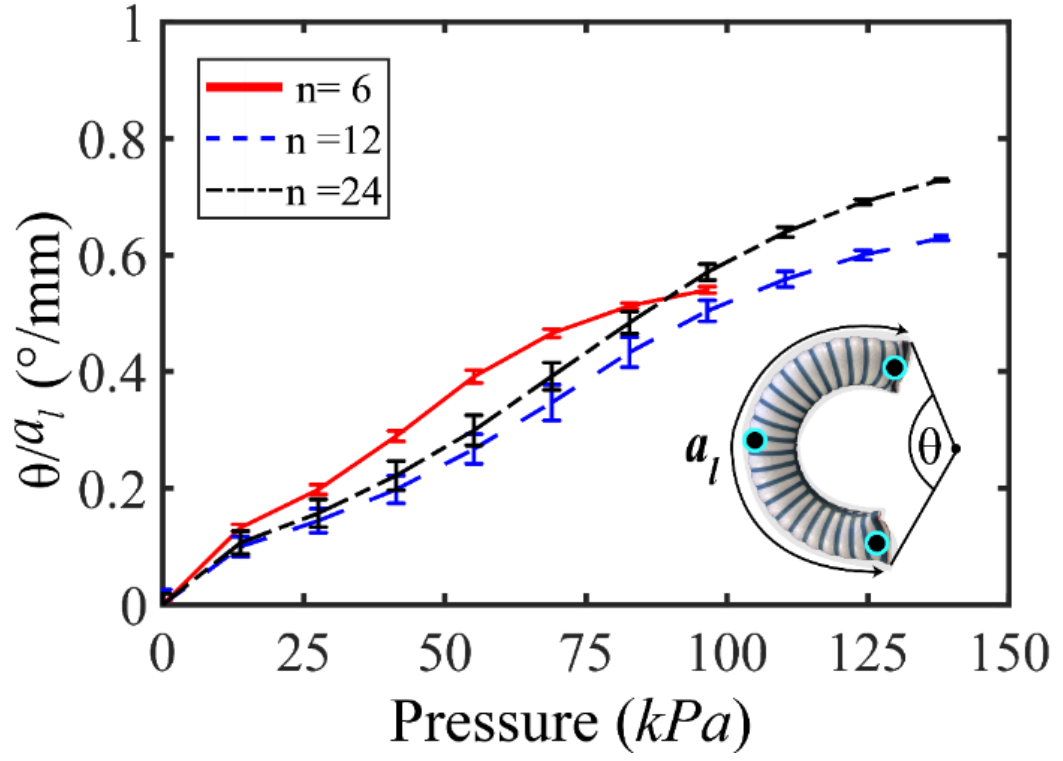
3.3 Results
3.3.1. Bending

Figure 5 Curvature angle per unit length for different fabric reinforcements (n)

Figure 4 shows the angle of curvature per unit length of the bending actuator. The maximum achievable bending state was achieved by *n=24*, achieved reaching 0.73°/*mm* at 137.9 *kPa*. In contrast the FRTA with *n=6* achieving 0.54°/*mm* at 96.53 *kPa*.
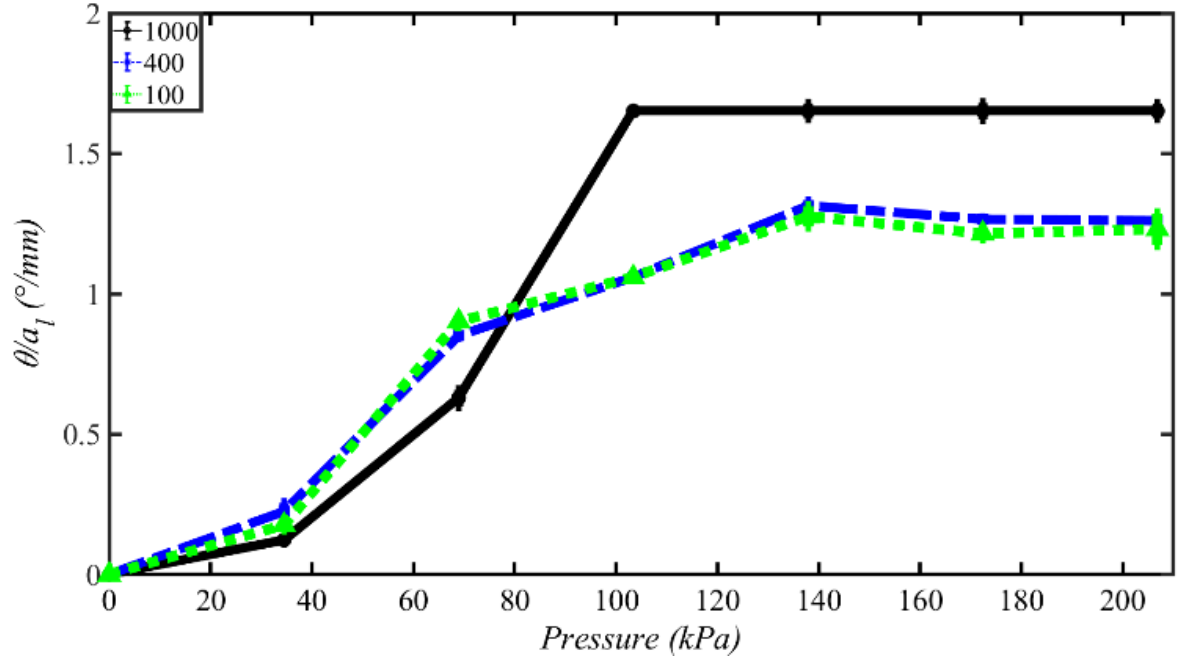
Figure 6 Curvature angle per unit length for different reinforcement materials

A one-way ANOVA was performed on the means of the reinforcement bands and the means for different materials reinforcements. For both the test indicated non-significance between the bending performance of the actuator for different reinforcement n or by changing the material of the reinforcement for bending performance for $p<0.05$. This was confirmed by also performing a two-sample t-test between the groups.

3.3.2. Extending

Figure 5 shows the angle of curvature per unit length of bending for materials with different deniers and *n=24*. The maximum achievable curvature was 1.65 °/mm at 103.2 kPa. The radial expansion remained similar to *n=24* reaching a maximum of 20% at its maximum pressure

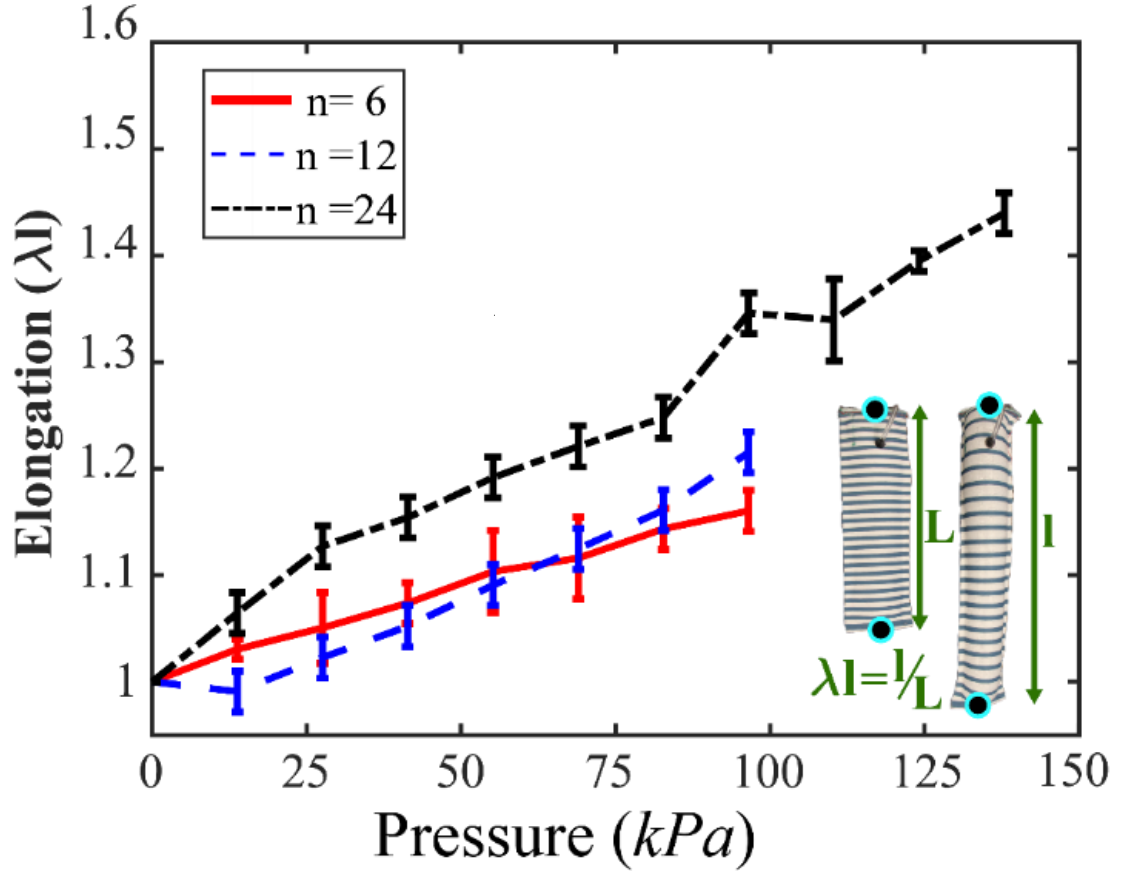*Figure 7 Evaluation of the extension capabilities (λ₁) of the FRTA for varying number of reinforcements (n). Markers are signified by the blue dots.*

Figure 6 shows the extension per unit length of FRTAs. The reinforcement of the actuator once again where *n=6,12,24*. The FRTA that experienced the greater extension was *n=24* increasing its original length by 44% of its initial length at 137.9 *kPa*. In contrast the

actuators with lesser number of reinforcements achieved both lower extension and lower maximum pressures both reaching having a maximum operational pressure of 96.53 *kPa* and achieving 16% and 22% extension respectively. The radial expansion followed a similar behavior to that of the bending actuators with increasing *n* decreasing the maximum radius achieved by the FRTAs at its maximum pressure.

A two-sample t-test was performed on *n=6* and *n=12* to try to extract a significant difference for changing the number of reinforcements. However, the test indicated non-significant difference ($p>.05$) in extending performance by increasing the number of reinforcements.
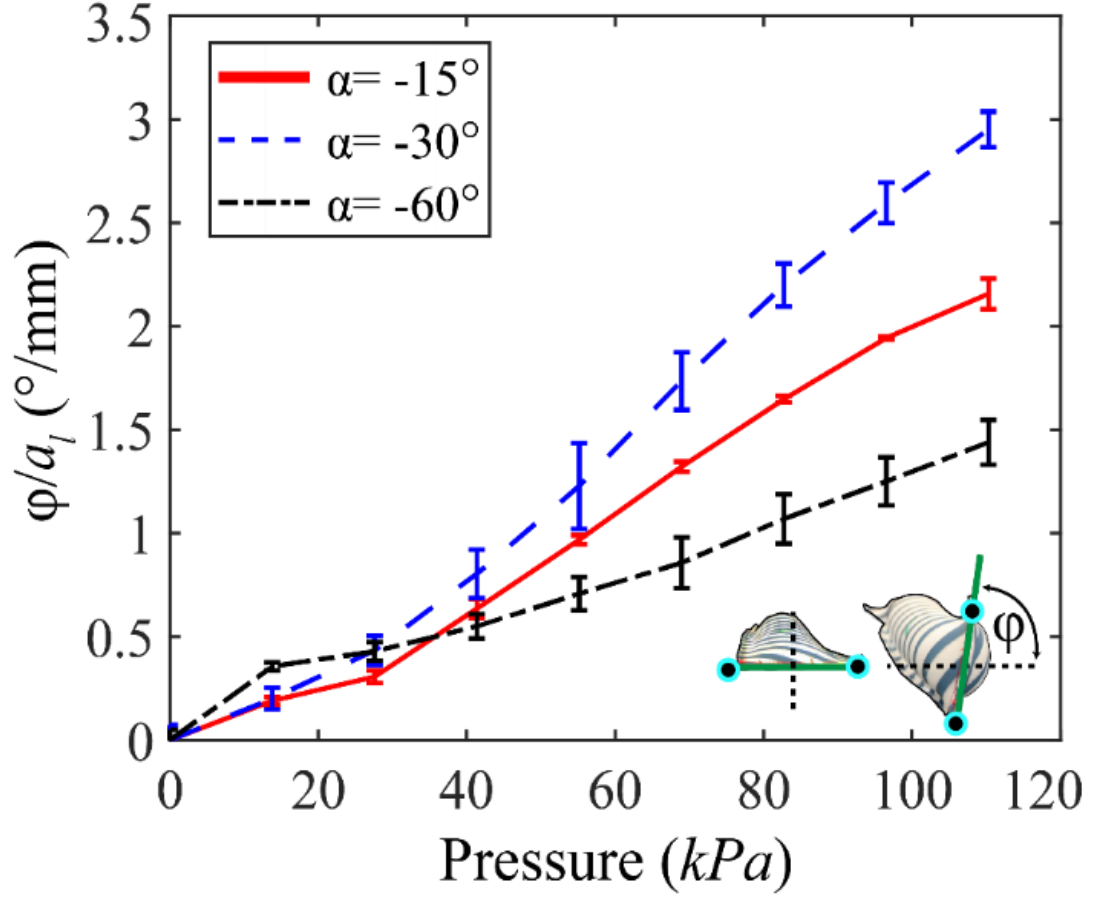
3.3.3. Twisting

Figure 8 Evaluation of the twisting capabilities of the FRTA for varying angle (α). Markers are signified by the blue dots.

Figure 7 shows the twist per unit length of the actuator. The FRTA with α=30° achieved the maximum twisting state of 87°/*mm* at 110.316 *kPa*. The radial expansion for these actuators as shown in Figure C follows similar trend to the bending actuator, however in here we can see that α=30° achieve a medial radial expansion. The actuator that experience the least twist per unit length was α=60°reacjomg barely 1.44°/*mm* which correlated with a twist of 43.2°. The least radial expansion was experience by α=15°, expanding by 27.6 %, while

$\alpha=60°$ experience the greatest expansion of 45.6% of its initial radius. As the testing for these actuators took place at the same time as the bending actuators an arbitrary $n=16$ was used to fabricate them.

A one-way ANOVA was performed to determine the statistical significance of changing the direction of the reinforcements. The test indicated no statistical significance between the groups ($p>.05$). This was confirmed by also performing a two-sample t-test between the groups.
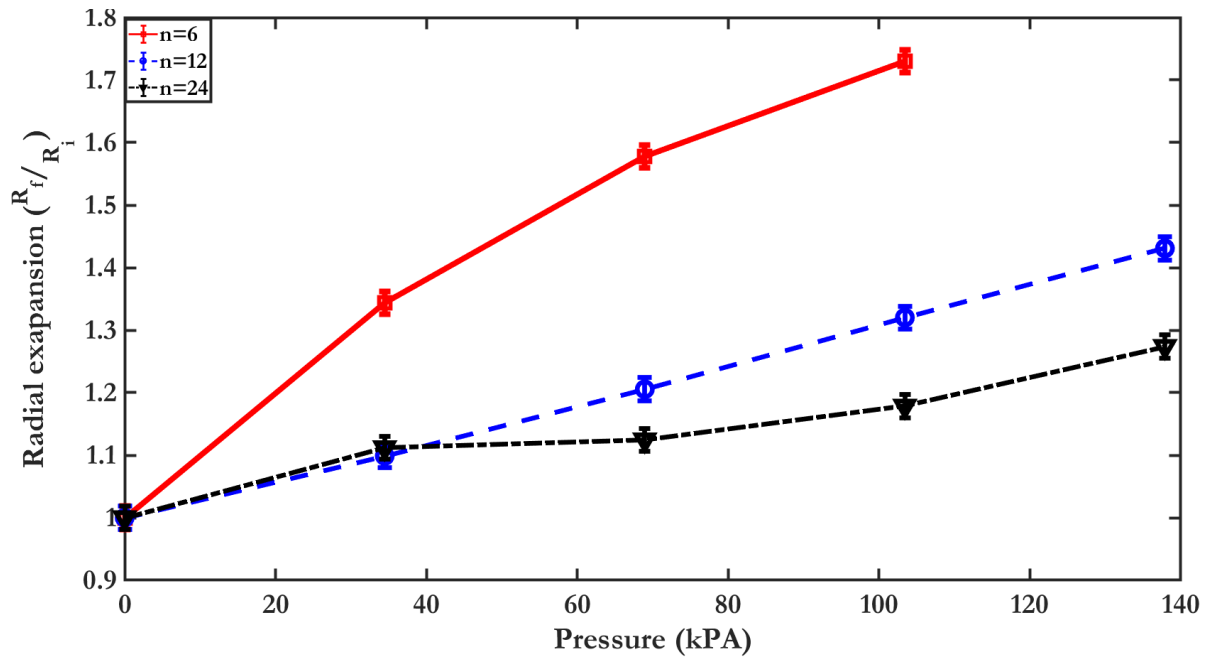
3.3.4. Radial Expansion

Figure 9 Radial expansion for bending FRTA for varying reinforcements (n).

Figure 8 shows the radial expansion as a percentage of the initial radius of the bending actuator for different number of reinforcements. The actuator with $n=6$ achieved expanded the higher expansion, expanding by 70% of its initial radius at 103.4 kPa. $n=12$ and $n=24$

reached a considerably lower final radius, expanding by 37.9% and 23.5% at 137.9 kPa respectively. The lower pressure achieved by less reinforcements was observed across all actuators tested.
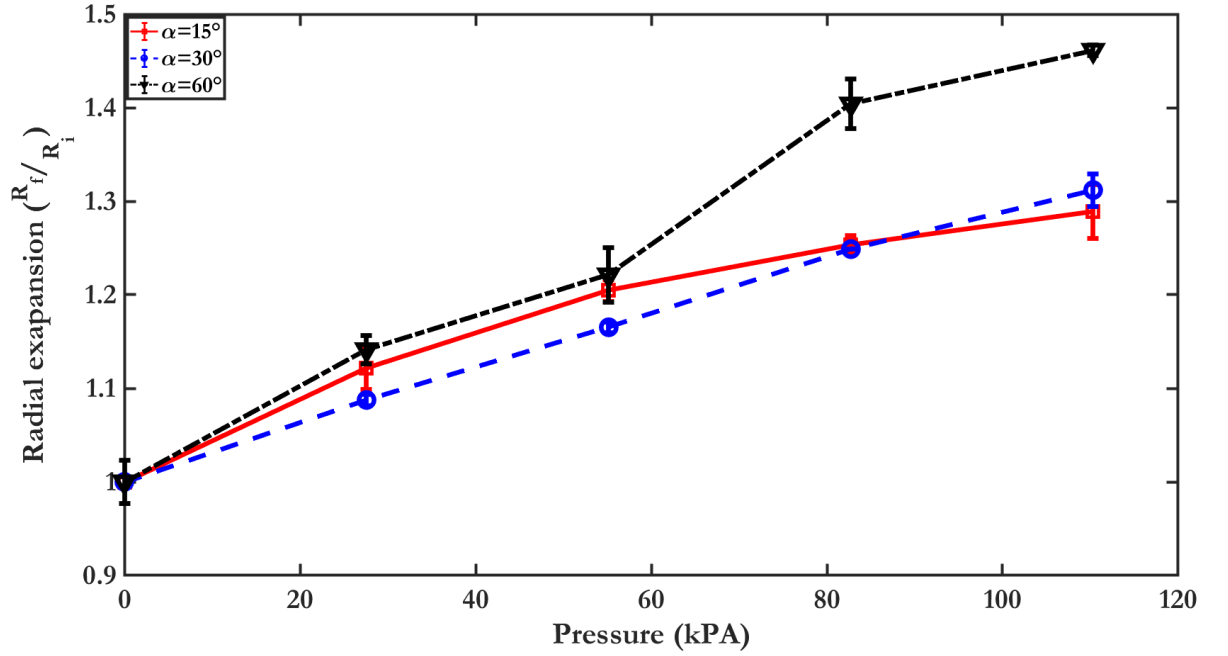

Figure 10 Radial expansion of twisting FRTA for varying angles *(a)*

Figure 9 shows the radial expansion as a percentage of the initial radius of the twisting actuator for different angles. The actuator with $\alpha=60°$ reached a maximum expansion of 46.5% of its initial radius. The other two $\alpha=15°$ and $\alpha=60°$ reached a similar expansion of 27.6% and 30.1%. The overall trend seems to indicate that the actuators expand less if the reinforcements are parallel to the direction of the stretch.
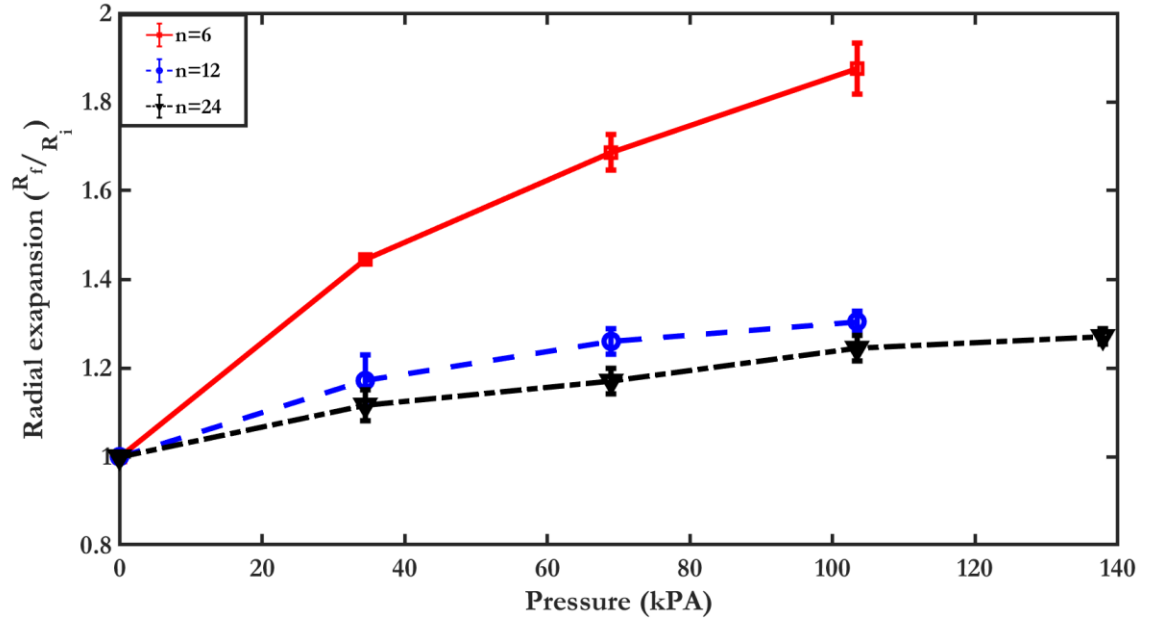
Figure 11 Radial expansion of extending FRTA for varying number of reinforcements (n).

Figure 10 shows the radial expansion as a percentage of the initial radius of the bending actuator for different number of reinforcements. The maximum pressure for the actuators with n=*6* and *n=12* was lower than the one for bending actuators achieving only 103.4 *k*Pa. The actuator with *n=6* once again achieved expanded the highest expansion, expanding by 87.4% of its initial radius, while *n=12* reached a considerably lower final radius, expanding by 30.5%. *n=24* reached a maximum expansion of 27.1% at 137.9 *k*Pa.

3.4. Discussion

3.4.1. Relationship between increasing reinforcements and motion performance.

The increase in the number of reinforcements was observed to decrease the radial expansion of the actuator. The decrease in radial expansion was also found to significantly

increase actuator performance from $n=6$ to $n=12$ with a marginal improvement from $n=12$ to $n=24$. It is observed that at lower pressures the actuators all exhibit similar bending curvatures with n_6 achieving a greater curvature than the

It is interesting to note that at lower pressures the actuators reach similar bending curvature with $n=6$ apparently surpassing the curvature from the other two actuators; however, this is clearly proven to be that this actuator reaches a much lower bending curvature when compared to $n=12$ and $n=24$ and achieves its maximum curvature at lower pressures.

3.4.2. Relationship between denier of material and performance.

As it can be seen in Figure 5 as the denier of the material reinforcement is increased the FRTA is able to reach higher pressures and bends more. Combined with the greater amount of reinforcement the relationship seems to indicate the

3.4.3. Relationship between α and twisting performance.

The relationship between alpha and the twisting performance of the actuator wasn't as clear cut as the relationship between n and motion. It is clear that the actuator performed better at twisting when the fabric reinforcements orientation was $\alpha=30°$. As α reached $60°$ its was noted that magnitude of the twist achieved was the lowest out of all three actuators tested. This behavior can be attributed to the fact that as the angle α increases the fibers of the high stretch fabric get constrain more longitudinally rather than radially. As it has been previously discussed actuator performance is greatly dependent on controlling the direction of the stretch. For the previous FRTAS it the reinforcements were perfectly perpendicular to the desired direction of the main stretch. However, as α is increased the direction of the reinforcements changes from restricting the radial expansion to restricting the axial expansion of the actuators.

As the actuators become more parallel to the longitudinal strain the restriction on the radial expansion decreases and the stretch used to move is restrained.

Thus, is can be assumed that twisting is achieved by reaching a balance between radial and longitudinal expansion of the fabric. From the results it can then be proposed that this equilibrium reaches its optimum state at around 30°.

3.4.5. Controlling radial expansion and durability and tolerable pressure

The durability, as well as the operational pressure of the actuator were found to be affected by its radial expansion. During testing it was noted that actuators with a lower number of reinforcements experience failure at a lower pressure. This can be attributed to the fact that even though the reinforcements greatly reduce the amount of localized stress by having a larger surface area than thread, the fabric still experiences localized stress at the location of the edges of the reinforcements. It is also observed that the most common failure point for bending and extending actuators was usually located its center.

4. ANTHROPROMORPHIC HAND

4.1. Design of the Anthro hand

To test the applicability of the FRTAs an anthropomorphic hand was created using two types of actuators, purely bending and twist-bend. The reason to imitate the human the architecture of the human hand is twofold: as far as it is known the human hand is one of the most versatile manipulators in nature and most ADL objects and tools have already been optimized for the shape of the human hand. As it was observed in the actuator characterization a lesser number of reinforcements reduce the FRTAs required pressure to achieve a bending state. Therefore, sections in the reinforcements were the n was decreased were used as knuckles for the fingers. This difference in segmentation allowed for a bending motion closer to the one perform by the human finger. Using this fact, less reinforcements were used at the location where the joints of the hand would be the MCP, PIP, DIP. The Bend-Twist was made not to imitate the anatomy but rather the motion of the thumb, primary the abduction of the thumb as this was determined to be a crucial component for adequate grasp. Figure 11 shows the design patterns of the "fingers".

The dimensions of the actuator were $l = 150$mm and $w = 78.54$mm, all fingers including the thumb shared the same dimensions. The reason for making all the fingers the same length was to simplify the fabrication of the gripper. However, it was observed during development that thanks to using a fingerless glove as the main body of the hand it was easy to change the position of the fingers to match the shape of the human hand. The gripper performed better when all the fingers were aligned therefore only this configuration is shown in this project. These dimensions were picked to closely mirror the dimensions of the average

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human finger. The main difference in between the purely bending and the bend twist FRTA was the pattern of the reinforcements.
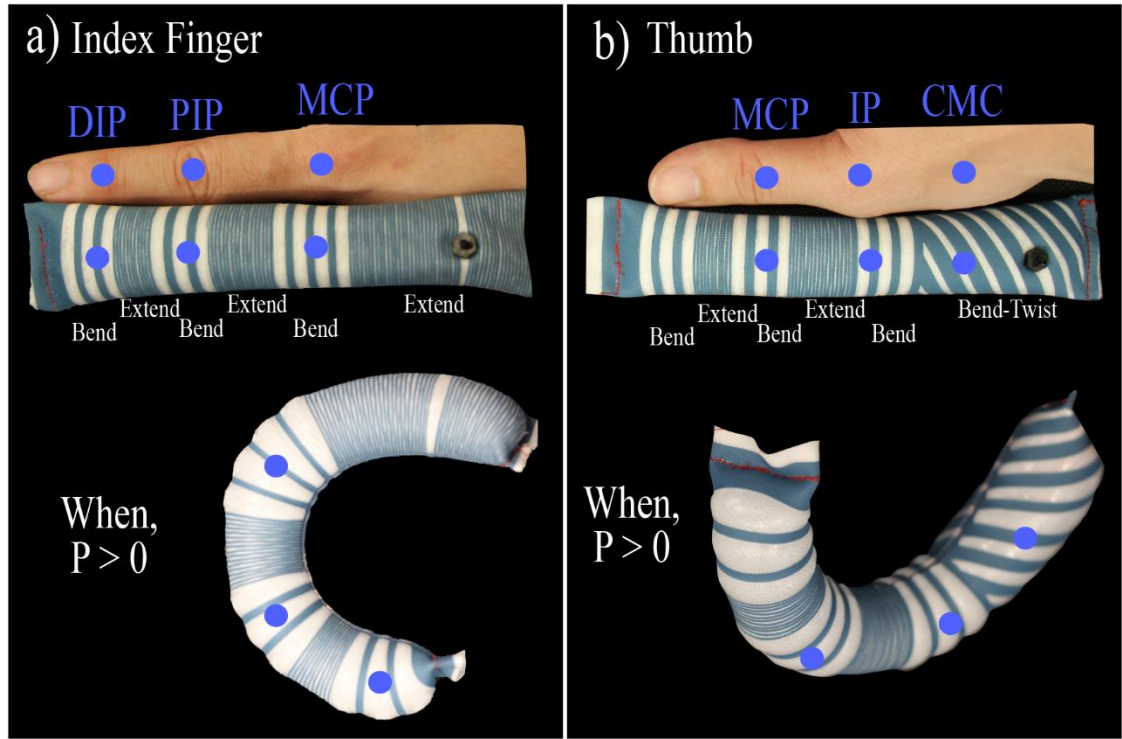

Figure 12 Segmented FRTAS: a) Multi-segmented FRTA to mimic the motion of the index finger b) Multi-Segmented FRTA to mimic motion of the thumb.

The bending motion of the actuator was observed to follow the same behavior as the one tested in section 3. The FRTA geometry was as follow, it can be divided into seven segments as shown in Figure 11, assigning 1 to the base segment it can be seen that the knuckles are even segments (2,4,6) the odd segments work as the phalanges in the human hand. For the phalange segments the reinforcements were closely packed together being set consecutively 1 mm apart. The knuckle segments had a greater separation between the segments each being 3 mm while the reinforcement was only 2.5 mm. The dimensions of each are shown in Table 2.

Table 2 Dimensions of the segments of the Finger bending FRTA.

Segment	Length (mm)
1	52.2
2	20.2
3	18.7
4	18.7
5	6.0
6	15.7
7	12.7

The dimensions of the patterns for the thumb remained the same except for the dimensions of segment 1. Segment 1 for the thumb consisted on the twist section of the actuator. To maximize the twist performance the reinforcements had a $\alpha=30°$, as it was shown during the testing segment this orientation was optimal for the twisting motion. It was noted that when combining the patterns, the change in radial expansion was different for different patterns so adjustments needed to be made to account for this the actuator would balloon up at the sections with the weaker segments reducing its performance.

The addition of the "knuckles", determined by the lesser amount of reinforcement used in these sections, made the bending curve sharper and closer match bending of the human finger. This behavior can be attributed to the fact that the lesser restrains on the knuckle sections allow the fabric to stretch further than the more heavily reinforced sections. The combination of these two sections serve to create a motion that when pressurized closely match the flexion of the index finger. For the twist-bend FRTA the actuator had a similar

pattern to the one for purely bending one, the key difference being a twisting section located at the base of the actuator to allow for "abduction".
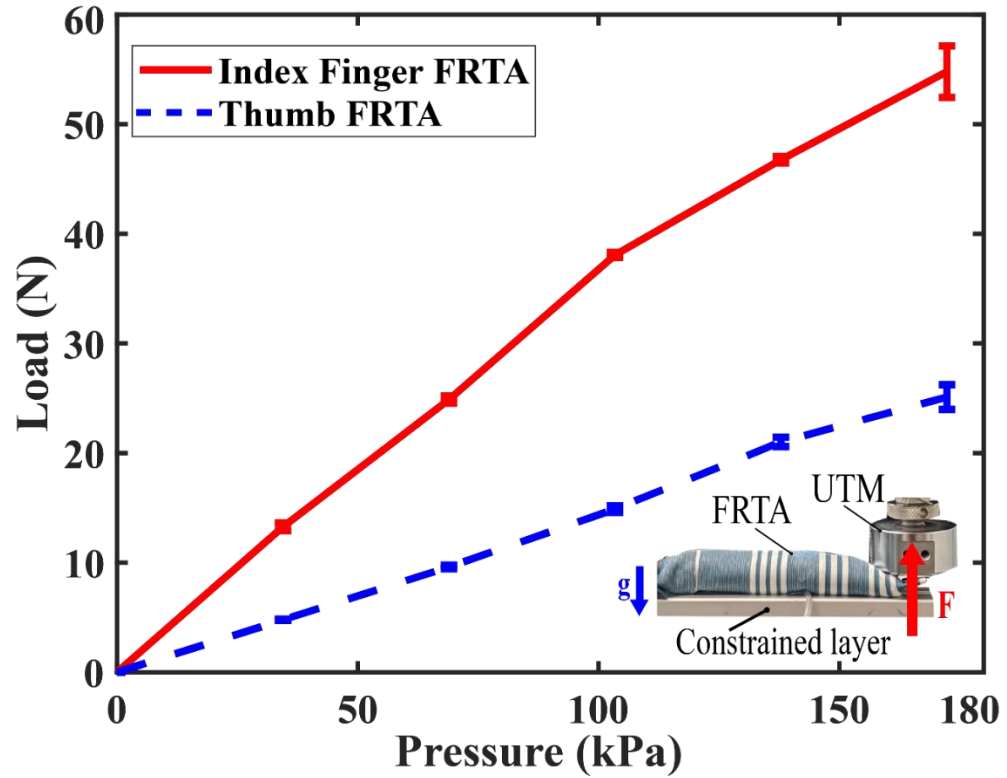

Figure 13: Payload capability of the index finger and thumb inspired FRTA up till 172 *k*Pa

Figure 12 shows the tip payload capacity of the bending fingers and the thumb FRTA. The fingers were tested by inflating the FRTA upwards from 0 to 172 *k*Pa in intervals of 34.5 *k*Pa against the load cell of the UTM. The maximum load generated by bending FRTA reached a maximum of 54.8 N. The maximum load generate by the thumb FRTA was 25.1 N. From this preliminary test it can observed that when combined the FRTAS could theoretically generate a force of 244.3 N. However, one has to consider that for FRTA the actuator will not just touch the object with its tips but will envelope the object with the whole body of the actuator.

4.2. The Full Hand

Figure 13 shows the completed design of the gripper. The fingers were then fitted with a stretchable fabric coated with a friction enhancing material (3M TB614, 3M Company, Maplewood, MN) to increase gripping power. A woven glove fitted with some foam padding was used to create the palm of the actuator. Each finger can be actuated individually, and the thumb was positioned so that it was in opposition to the little finger.
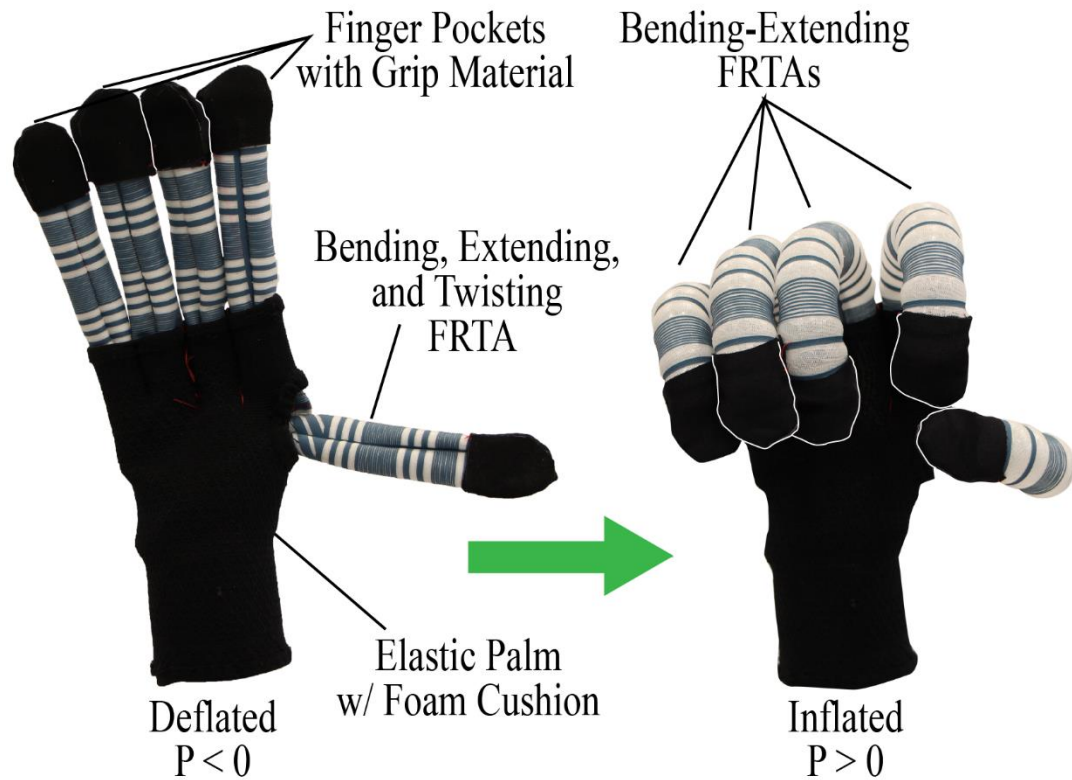
Figure 14 Left: Deflated soft robotic hand. Right: Inflated soft robotic

The total weight of the hand was 89 *g*. The grasping performance of the gripper by having it grip six different objects from daily life show in Figure 14. The objects picked up by the gripper were an apple (168.5g), a box (134g), a metal bottle (165g), a cup (50.3g), a sea shell (94.1g) and a cleaning bottle (93g). All of these objects had different surface properties and geometries, thus providing a good estimate of the capabilities of this design. As it can been

seen from the figure the current method by which the hand manipulate objects is by doing a power grasp. Due to the compliance of the materials used this present no problems when the goal is to simply pick up an object; however, if the task requires precise manipulation or dexterous motion of the object the current controls of the hand are not optimal for these tasks.
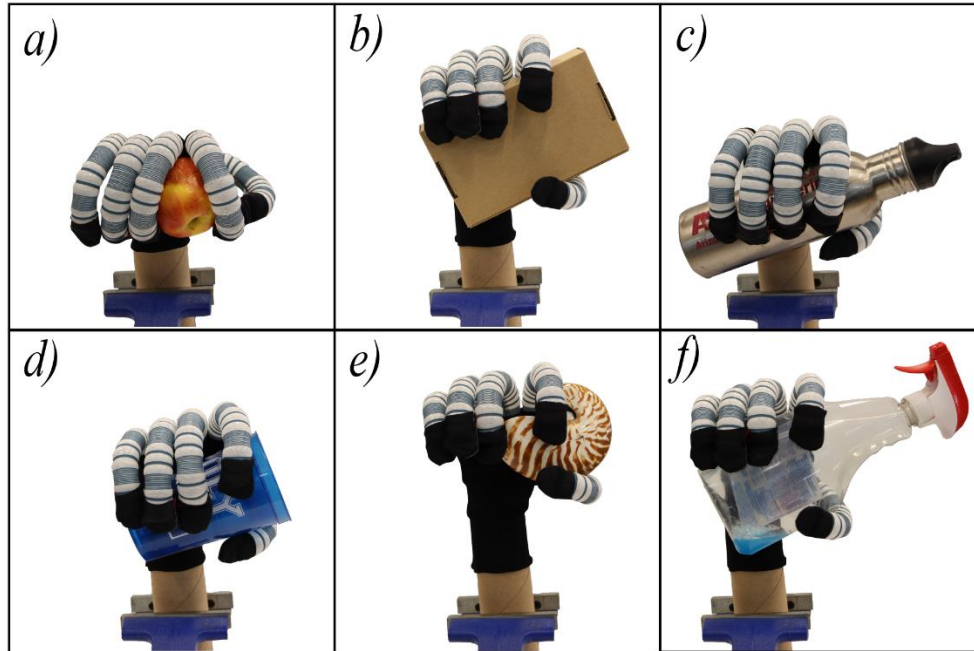
Figure 15 Grasping a variety of objects: Grasping a variety of objects. *a) Apple (168.5g) b) Box (134g) c) Metal Bottle (165g) d) Cup (50.3g) e) Sea Shell (94.1g) f) Cleaning Bottle (93g).*

5. CONCLUSION AND FUTURE WORK

The purpose of this research was to develop a new type of fabric-based actuators to be used in the fabrication of a gripper for ADL. The result was the development of the FRTA, actuators that using the concept of anisotropic strain and textile layering can be mechanically programmed to generate a wide variety of motions. The behavior of the FRTA will depend on the design of its reinforcement layer. The FRTA succeeded in being a lightweight mechanically programmable fabric-based actuator. As far as the author is aware this work is the first one to implement the concepts of FRA into textiles actuators.

The FRTA is fabricated using inexpensive fabric materials that allow for 2-D manufacturing making the process of making the actuators relatively simple. The methods allow for the rapid prototyping of various designs and while the designs explored in this project are by no means exhaustive, they provide a good reference frame of the overall behavior of the actuator. This can be used in future work to accelerate the prototyping of new types of FRTA. The main parameters to keep in mind for the development of this actuator are the strain of the stretchable layer, the overall strength of the reinforcement layer, inclusion of a strain limiting section, the number and direction of the reinforcement bands. As it was shown the greater the strength and the number of reinforcements allow the FRTA to achieve greater pressures and movements by means of constraining its radial expansion, focusing the strain on the longitudinal direction.

The main objective of this technology is to be used as the fingers of soft robotic grippers. Due to versality and the ease of changing the parameters of the actuators the designers will not be limited to either make the gripper task centric or human centric.

The FRTAs are at an early stage in their development, and the development of a mathematical model to accurately predict is behavior will be needed before improvements can

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be made to this technology. The development of a mathematical model will also aid in exploring different configurations of reinforcement patterns without having to fabricate the prototype to obtain an initial estimate of how the design will make the actuator move. More intensive grasping tests are needed to validate the efficiency of the actuator at picking a wider array of objects and at imitating different human hand postures. There is a need to optimize the material and the pattern selection of the FRTA. There is also room to better combine patterns to generate complex motions for a single actuator. For the gripper to be usable for stroke patients there is also a need to incorporate sensors that at least give the actuators some kind of feedback about user intent. The FRTAs would also benefit from the inclusion of a strain sensor into the actuator itself, not only could this be used to better study the behavior of the actuator, but it could also be used for better controls.

The long-term goal of the FRTA is to use it to build a robust grasper for a soft poly limb (SPL) that has been developed by the ASU Bio-Inspired Mechatronics lab [37]. This SPL was developed with the goal of assisting patients with upper limb impairment carry out their activities of daily living. As of now it has been shown the arm is capable of effectively performing a wide array of motions and when combined with a suction cup can be used effectively to pick and place various objects. Adding a more dexterous end effector using the FRTA developed in this thesis would increase the applicability of the SPL.

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