Flexible Fluidic Actuators for Soft Robotic Applications

Weiping Hu

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Flexible Fluidic Actuators for Soft Robotic Applications

Weiping Hu

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School of Mechanical, Materials, Mechatronic and Biomedical Engineering

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Abstract

An emerging topic in robotics research is the development of a robot with soft characteristics to perform complicated locomotion in various environments. Developing an actuator that can be used in soft robotics is a bottleneck in robotics research. Soft pneumatic actuators (SPAs) offer significant potential to be used in soft robotic applications, especially for bio-inspired robots, because of their remarkable properties of compliance and inherent safety. To realise these soft robotic applications, there is an increasing need to design, optimise and fabricate function-specific flexible pneumatic actuators. Therefore, the objectives of this thesis were to establish a methodology for structural optimisation of SPAs and develop pneumatic actuation systems with a specific function that could be used in various soft robotic applications.

A comprehensive literature review of actuators was undertaken, with a particular focus on the mechanisms, applications towards soft robotics and fabrication of SPAs to identify the design requirements and basic knowledge of the primary type of actuators used for soft robotics. SPAs have attracted much research interest for various soft robotic applications; however, further research on flexible pneumatic actuation design, optimisation and applications is necessary to gain an in-depth understanding of SPAs and broaden their applications. Further improving fabrication methods for soft robotic applications is required to enable it for direct printing various application without any post-fabrication process.

This thesis reports on designing, optimising and fabricating flexible pneumatic actuators for soft robotic applications. With a uniaxial tensile test following the ISO 37 standard, this research characterised the properties of materials used to fabricate the soft actuator, including ELASTOSIL M4061, Ecoflex 00-10, soft translucent silicones and FilaFlex. The abilities of seven general hyperplastic models—Mooney-Rivlin, neo-Hookean, Polynomial, Blatz-Ko, Arruda-Boyce, Yeoh and Ogden models—were compared and analysed, both theoretically and experimentally. A methodology for structural optimisation based on statistical analysis was proposed to investigate the effects of primary design parameters on the performance of the pneumatic actuator to be used in soft robotic applications. This research evaluated the effects of the structural
parameters—including the operation pressure, wall thickness, gap between the chambers, bottom layer thickness and geometry of the channel cross-section—on the deformation and bending angle of the actuator. A global analysis of variance was performed using a finite element method (FEM) to systematically study how the parameters affected the behaviour of the actuators. This optimisation method could be extended to other designs of pneumatic actuators to develop novel multi-functional soft robotic applications.

To expand the applications of SPAs, this study developed a new bio-inspired, 3D-printed, low-cost, all-in-one, fully compliant SPA consisting of a series of internal chambers with the same helix angle that generated helical (bending and twisting) motions in 3D. The trajectory of the helical actuator was characterised by changing the angle of the chambers and length of the actuators using FEM. The 3D printing settings were optimised for direct printing of the airtight soft actuator with commercially available hyperelastic materials. Experimental measurement and numerical calculation of the blocking force were performed. The behaviours of the helical actuator were compared with those of bending actuators, but with the same size (i.e., a typical bending actuator generating a two-dimensional trajectory). The results indicated that the proposed helical actuator had a higher mechanical efficiency than the bending actuator under the same pressure input. After modelling, different design concepts—such as a bidirectional bending actuator generating symmetrical twisting motion, rehabilitation finger application imitating the configuration of a real human hand, and soft robotic hand gripper—were developed to explore the potential of SPAs to be used in soft robotic applications. Based on the design and fabrication methods, a fully compliant soft gripper with four fingers made of helical actuators was demonstrated and used to grasp and lift complex shapes. It follows that the proposed method can be employed to build active structures (fingers) for a specific application and function. The proposed design and fabrication technique can contribute to building application- and function-specific soft robotic systems.
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Last, but not least, a huge thanks to my parents, who have given me unconditional love and endless support throughout my whole life. I would not have been able to overcome many challenges and eventually complete this thesis without their support. They make this work even more meaningful.
Certification

I, Weiping Hu, declare that this thesis submitted in fulfilment of the requirements for the conferral of the degree Doctor of Philosophy, from the University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualifications at any other academic institution.

Weiping Hu
1st July 2019
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>2D</td>
<td>Two-dimension</td>
</tr>
<tr>
<td>3D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>ABS</td>
<td>Acrylonitrile butadiene styrene</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of variance</td>
</tr>
<tr>
<td>BISMAC</td>
<td>Bioinspired shape alloy composite</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Assisted Drawing</td>
</tr>
<tr>
<td>CNC</td>
<td>Computer numerical controlled</td>
</tr>
<tr>
<td>CNTs</td>
<td>Carbon nanotubes</td>
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<tr>
<td>DEs</td>
<td>Dielectric elastomers</td>
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<tr>
<td>DMD</td>
<td>Digital mirror device</td>
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<tr>
<td>DOF</td>
<td>Degrees of freedom</td>
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<tr>
<td>EAPs</td>
<td>Electroactive polymers</td>
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<tr>
<td>ERFs</td>
<td>Electrorheological fluids</td>
</tr>
<tr>
<td>FEAs</td>
<td>Fluidic elastomer actuators</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite element method</td>
</tr>
<tr>
<td>hMSCs</td>
<td>Human mesenchymal stem cells</td>
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<tr>
<td>IPMC</td>
<td>Ionic polymer-metal composite</td>
</tr>
<tr>
<td>MEMS</td>
<td>Microelectromechanical systems</td>
</tr>
<tr>
<td>MREs</td>
<td>Magnetorheological elastomers</td>
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<tr>
<td>PAM</td>
<td>Pneumatic artificial muscle</td>
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<tr>
<td>PBA</td>
<td>Pneumatic balloon actuator</td>
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<tr>
<td>PDMS</td>
<td>Polydimethylsiloxane</td>
</tr>
<tr>
<td>PEGDA</td>
<td>Poly (ethylene glycol) diacrylate</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>--------------</td>
<td>---------------------------</td>
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<tr>
<td>PLA</td>
<td>Polylactic acid</td>
</tr>
<tr>
<td>PneuNets</td>
<td>Pneumatic networks</td>
</tr>
<tr>
<td>SMAs</td>
<td>Shape memory alloys</td>
</tr>
<tr>
<td>TPE</td>
<td>Thermoplastic elastomer</td>
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>A</td>
<td>Area of inside the channel</td>
</tr>
<tr>
<td>$A_w$</td>
<td>Cross-sectional area</td>
</tr>
<tr>
<td>d</td>
<td>Material incompressibility parameter</td>
</tr>
<tr>
<td>J</td>
<td>Determinant of the elastic deformation gradient</td>
</tr>
<tr>
<td>C$ij$</td>
<td>Material constants</td>
</tr>
<tr>
<td>d$k$</td>
<td>Material constants</td>
</tr>
<tr>
<td>E</td>
<td>Modulus of elasticity</td>
</tr>
<tr>
<td>F</td>
<td>Force</td>
</tr>
<tr>
<td>I</td>
<td>Area moment of inertia</td>
</tr>
<tr>
<td>I$_1$</td>
<td>First deviatoric strain invariants</td>
</tr>
<tr>
<td>I$_2$</td>
<td>Second deviatoric strain invariants</td>
</tr>
<tr>
<td>N</td>
<td>Material constants</td>
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<tr>
<td>N.A.</td>
<td>Neutral axis</td>
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<tr>
<td>P</td>
<td>Pressure</td>
</tr>
<tr>
<td>R</td>
<td>Radius of the curvature</td>
</tr>
<tr>
<td>r</td>
<td>Winding radius</td>
</tr>
<tr>
<td>S</td>
<td>Arc length</td>
</tr>
<tr>
<td>t</td>
<td>Range of the loops</td>
</tr>
<tr>
<td>W</td>
<td>Strain energy per unit reference volume</td>
</tr>
<tr>
<td>b$ij$</td>
<td>Bond strength</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Initial shear modulus of the material</td>
</tr>
<tr>
<td>$\lambda_L$</td>
<td>Limiting network stretch</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------</td>
</tr>
<tr>
<td>$\lambda_P$</td>
<td>Principal stretches of the left Cauchy-Green tensor.</td>
</tr>
<tr>
<td>$\overline{\lambda}_P$</td>
<td>Deviatoric principal stretches</td>
</tr>
</tbody>
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Chapter 1

Introduction

1.1 Introduction and Motivation

Robots are classified into rigid and soft types according to the compliance of the material of which they are made and their functions. Traditionally, rigid robots are widely used in industry for their high efficiency; however, this comes with the disadvantages of high cost and lack of adaptability and compliance when interacting with their immediate environment. Soft robots are expected to replace rigid robots in various applications and to play an increasingly significant role in the field of artificial intelligence because they offer safe contact and interaction with their physical environment.

Soft robots can generate continuum deformations and they are assumed to have the following features: (i) they should be safe to interact with humans, (ii) they should be easy to fabricate, (iii) they should be lightweight, (iv) they should have low-cost fabrication and maintenance, (v) their actuation and control system should be simple and (vi) their environmental footprint should be small. Over the last few decades, there have been a large number of alternative approaches aiming to achieve these goals. The development of soft robotics has had a significant effect on progress in medical applications that require human–machine interaction [4]. Future robots are envisioned to be bio-inspired soft robots with soft actuators that can achieve soft, flexible movements and can safely interact with people.

The capabilities of soft robots strongly depend on the performance of actuators, and the main problem with the traditional actuation mechanism is the lack of flexibility. A soft flexible actuator provides the unique promise of adaptive and inherently safe systems. The features of soft flexible actuators are particularly important in soft robotic applications. Thus, it is necessary to develop and optimise a low-cost, soft and flexible actuator that can accomplish various tasks, as will be conducted in this thesis.
1.2 Aims and Objectives

This research aimed to establish a pneumatic actuation system with a specific function for soft robotic applications. Both experimental and computational studies were conducted to realise the aims of this research. Specifically, the objectives of this research were as follows:

- This research aimed to characterise the hyperelastic materials used to fabricate the soft actuator. This included determining a suitable strain energy function for the soft materials to be used in soft robotic applications. The stress–strain behaviour was experimentally tested through a uniaxial tensile test system, following ISO 37 standard. Moreover, a comprehensive comparison of seven commonly used hyperelastic models—the Mooney-Rivlin, neo-Hookean, polynomial, Blatz-Ko, Arruda-Boyce, Yeoh and Ogden models—was conducted. The material properties were analysed through the finite element method.

- This research aimed to investigate the effects of various design parameters on the performance of the pneumatic bending actuators with discrete chambers and to optimise the design of the chambers. This research examined the effects of several essential design structural parameters—the operation pressure, wall thickness, gap between the chambers, bottom layer thickness and geometry of the channel cross-section—on the deformation and bending angle of the actuator. To understand how the variables affected the mechanical output of the actuator and which variables significantly affected the deformation or bending angle, a global analysis of variance (ANOVA) was performed.

- To improve the functions of fully compliant pneumatic network actuators, this research designed and fabricated a novel soft pneumatic helical actuator. To gain a better understanding of the bending and twisting behaviour of this soft helical actuator, the trajectory was characterised by changing the design parameters. The fused deposition modelling (FDM) technique was used to manufacture the actuator, and the printing settings were optimised to directly print the thin-wall, airtight 3D helical actuator.
To expand the applications of soft pneumatic actuators (SPAs), this research developed different design concepts, such as a bidirectional bending actuator, rehabilitation finger application and soft robotic hand gripper. Based on this actuation concept, this research experimentally demonstrated a fully compliant soft gripper with four fingers made of the helical actuators.

### 1.3 Thesis Outline

This thesis is organised into seven chapters as the flowchart shows in Figure 1.1. Following this introductory chapter, an extensive literature review is presented in Chapter 2, which discusses the existing flexible actuators for soft robotics and currently available fabrication methods. This highlights the necessity of the work conducted in this thesis. Chapter 3 presents the experimental test and finite element modelling of hyperelastic materials conducted to guide the selection of suitable modelling functions for hyperelastic materials used in soft actuators. Chapter 4 presents the methodology for structural optimisation of SPAs, in which the relevant parameters involved in the actuator design are considered, and the methodology is verified through both experimental and computational studies. Chapter 5 demonstrates a bio-inspired 3D-printed helical SPA, and discusses the fabrication of a gripper, while Chapter 6 presents several smart structures using pneumatic actuators. Finally, Chapter 7 presents the major findings and conclusions of this work, alongside suggestions for future research.
1.4 Principal Contributions

This study presented in this thesis makes important contributions to the field of soft pneumatic actuators for soft robotic applications. The principal contributions of this thesis are as follows:

- The mechanical behaviours of four hyperelastic materials, including ELASTOSIL M4061, Ecoflex 00-10, soft translucent silicones and FilaFlex, were studied theoretically and experimentally to characterise hyperelastic materials and determine a suitable strain energy function.

- Finite element analysis and experiments were conducted to investigate a methodology for structure optimisation of the soft pneumatic actuators, which provided the feasibility of designing and optimising smart structures through finite element method for the pneumatic bending actuators.
• A new bio-inspired, 3D-printed, low-cost 3D helical actuator based on multiple optimised longitudinal array of angled pneumatic chambers with a one-step manufacturing process was proposed to expand the applications in fully compliant soft robotics. The proposed design and fabrication technique contribute to establish application- and function-specific soft robotic systems.

• Different design concepts based on the comparison of simulation and experimental work, including bidirectional bending movements, rehabilitation finger applications, and soft robotic hand grippers, were proposed to demonstrate the ability of SPAs to achieve complex movements and develop soft robotic applications.
Chapter 2

Literature Review

2.1. Introduction

An emerging topic in robotics research is the development of a robot with soft characteristics to perform complicated locomotion and tasks in various environments. Figure 2.1 illustrates the difference between soft and rigid robots. Soft-bodied creatures have inspired many researchers to develop soft robots with a soft structure to imitate the outstanding capabilities of soft-bodied creatures. Worms, snakes, elephant trunks, jellyfish and octopus arms have been important inspirations for researchers to develop locomotion concepts. Traditionally, rigid robots have been widely used in industry because of their high efficiency and accuracy; however, this comes with the disadvantages of high cost and lack of adaptability and compliance when interacting with their immediate environment.

![Figure 2.1. Illustration of the fundamental difference between soft and rigid robots for manipulation and positioning tasks](image)

An actuator is a mechanical device that can generate a useful mechanical output when operated by an energy source. Developing an actuator that has a similar function with real natural muscle remains a bottleneck in robotics. Compared with conventional actuators, soft actuators can generate more flexible motions [4]. Typically, there are two classes of soft actuators for soft robots: smart actuators (made of shape-memory alloy, electroactive polymers, magnetorheological elastomers and electrorheological fluids) and flexible fluidic actuators (hydraulic and pneumatic actuators). Over the last few
decades, establishing new actuation concepts for soft robotics has been an active research topic in medical and engineering research fields. This chapter presents a comprehensive literature review to identify the design requirements for the actuation concepts, update the current status of actuators for soft robotics and determine the vital challenging issues in this field. Several commonly used fabrication methods for soft robotics applications are summarised.

2.2. Actuation Mechanism of Actuators Based on Smart Materials

This section primarily focuses on actuators made of smart materials, such as shape-memory alloys (SMAs), electroactive polymers (EAPs), magnetorheological elastomers (MREs) and electrorheological fluids (ERFs). The advantages and disadvantages of these two soft actuator groups and their properties are presented to provide a comprehensive account of challenging research issues regarding soft actuators.

2.2.1. Shape-memory alloy actuators

SMA actuators are widely used in the field of soft robotics research because of their unique features. In general, after plastic deformation at low temperature, a SMA returns to its original configuration upon the supply of heat. The phase changes from martensite to austenite, generating a contraction force and causing the SMA to return to its original position. The main characteristic of the materials is that they can ‘remember’ their initial configurations. Thus, the SMA actuation method can provide continuous bending and twisting movements. SMA actuators are favoured because of their ability to generate large displacements with simple mechanisms.

![Figure 2.2. Mechanism of SMA-based bending actuator [6].](image)
The first SMA (Au-Cd) was recorded by Arne Ölander in 1932 [7]. The Au-Cd alloy can generate plastic deformation at low temperature and return to its original position when heated. In the following decades, several SMA alloys—such as Cu-Al-Ni, Cu-Zn, Cu-Ti and Fe-Mn-Si—that can generate a similar phenomenon were discovered [8-10]. Although there are several kinds of SMAs, nickel–titanium (NiTi) is widely used and has proven to be the most flexible and suitable for soft robot applications [11]. The basic actuation of NiTi wire is generated by the heat produced by electric current, as shown in Figure 2.2 [6]. NiTi-based low-cost alloys can generate greater compliance, stable transformation temperature, proper recoverable motion and good biocompatibility, which is preferable for soft robotic applications.

The advantages of SMA actuators have provided new possibilities for soft robotics to perform complex locomotion and movements. The SMA actuator is a good choice for soft robotics and can be used in numerous applications. These actuators are widely used in bio-inspired compliant locomotory robots, as shown in Figure 2.3.

Over the last few decades, numerous researchers have developed many bio-inspired underwater soft robots with different sizes and functions. Generally, underwater vehicles for locomotion are inspired by soft-bodied marine animals, such as fish, jellyfish and octopi. Zhenlong Wang et al. [12] developed a micro-robot fish actuated by a biomimetic fin. SMA wires were used as fins in the micro-robot fish, since they can move flexibly and noiselessly. The researchers also developed a biomimetic robot squid [13] and manta ray robot fish [14] actuated by SMA wire, which can bend flexibly. Alex Villanueva et al. used a bio-inspired shape alloy composite (BISMAC) actuator, made of silicone, SMA wires and spring steel, to create an autonomous jellyfish—shown in Figure 2.3 (e)—that could move over large distances for a relatively long time [15]. The BISMAC actuators can convert larger deformation than can standard SMA, which is suitable for various design requirements. BISMAC has been employed to achieve the desired actuation for biomimetic jellyfish applications. Similar applications inspired by jellyfish actuated by the BISMAC actuator have been developed [16], and other jellyfish-inspired underwater robots with SMA have been proposed [17, 18].
Figure 2.3. (a) Bio-inspired wormlike robot using a NiTi SMA actuator [19]. (b) Caterpillar-inspired soft-bodied rolling robot [20]. (c) Jellyfish using a bio-inspired shape alloy composite actuator [15]. (d) Octopus arm [21]. (e) Actuation and shape recovery cycle of the SMA actuator used in prosthetic devices [22].
Another important source of inspiration for soft robotics is an octopus because of its soft structure and unique biomechanical characteristics. Octopus arms can move flexibly over a wide range and provide multi-degrees of freedom. Many octopus-inspired soft robots with SMA actuators have been developed. One example is an entirely soft and compliant robot arm, where SMAs are designed longitudinally and transversely to imitate the movements of biological octopus arms [21, 23]. The arm can elongate and shorten at longitude direction and bend in all directions, with large deformation and stiffness in water. A similar approach using SMA to imitate the octopus muscular hydrostats has been presented in previous research [21, 24, 25]. As a result of changeable stiffness and flexible soft bodies, octopus arms have the ability to perform various movements. The main advantages of SMA for underwater robots include its high force density, simple control system and high-frequency response. The major drawbacks are its high power and low efficiency.

Many worm-inspired soft robots have also adopted SMA actuators. Previous research developed a small crawling robot inspired by Caenorhabditis elegans [26]. A thermal SMA actuator was used because of its similar functions to the Caenorhabditis elegans muscles. Many similar applications using SMA actuators inspired by worms have been reported during the last few decades, such as an omega-shaped inchworm-inspired crawling robot [27], a caterpillar-inspired soft-bodied rolling robot [20], a 3D-printed Manduca sexta–inspired crawling locomotion robot with variable friction legs [28] and a biomimetic robotic earthworm [29]. Lately, Seok et al. presented a peristaltic locomotion wormlike soft robot with a flexible mesh-tube NiTi coil actuator [30]. They used an SMA spring actuator to imitate the movements of worms. Thin SMA wire coils are commonly used to improve the strain. This structure also allows the wire to move more flexibly. SMA actuators are also popular actuators for grasping devices [6, 22, 31-38].

The performance of SMA actuators is limited by their small output force and low efficiency. Force in SMAs is generated by temperature change, yet a high heating temperature easily damages SMA wires. In addition, the wire itself wastes most of the input energy; therefore, the efficiency is relatively low (about 1%). Recently, researchers have been focused on improving the efficiency and stability of the actuators.
2.2.2. Electroactive polymers

EAPs, as one type of electrically responsive smart materials, are one of the most attractive choices for soft sensors and actuators. EAP actuators, also known as EAP artificial muscles, are commonly used in soft robotics because of their similar behaviour to natural muscles. EAPs have many desirable features that can be employed by soft robotics, as they are flexible, cheap, lightweight, noiseless, biocompatible and easy to fabricate, and they consume a low quantity of electrical power [39]. EAPs are also popular choices for artificial muscles [40].

The size or shape of EAPs will change when activated by an electric field. EAPs can generate large deformation under large forces. Moreover, they are widely used in sensors and actuators as a smart material. In terms of the different materials and actuation mechanisms used, EAP materials generally include two categories: ionic and electronic EAPs.

2.2.2.1 Ionic electroactive polymers

The actuation of ionic EAPs is generated by the displacement of ions. Ionic EAPs are divided into four main classes: polymer gels, ionic polymer-metal composites (IPMC), conductive polymers and carbon nanotubes (CNTs) [41, 42]. Ionic EAP is attracting the attention of many researchers because of its extremely low operation voltage; however, more research is required to improve its efficiency with a long lifetime and rapid response. As a result of compliance and ease in processing, actuators made of EAPs are potentially useful for various bio-inspired and micro soft robotic applications. Ionic EAPs present significant advantages to be used as artificial muscles [43] because they have a similar size and shape change to natural muscles.

Moreover, ionic EAP actuators have attracted the attention of researchers who are concentrating on actuators for biomimetic underwater robots [44-47]. IPMC is a popular actuator used in underwater robots and several fish-like robots. For example, previous research developed a biomimetic tadpole fish using ionic polymer-metal composite [44]. The robot fish had an internal power source and control system and was able to perform high thrust. The bending motion, when applied with an electric field, is illustrated in Figure 2.4. A jellyfish-inspired robot based on the IPMC actuator was
presented in [45]. Thermal treatment was used to achieve the bending motion of the jellyfish and assist the actuator with constant curvature. The researchers observed and compared the vertical floating displacement and floating velocity (between 0.045 and 0.057 mm s\(^{-1}\)). Later, Joseph Najem et al. [46] developed a jellyfish robot aiming to obtain a higher speed (maximum 1.5 mm s\(^{-1}\)) and locomotion efficiency. Then they improved the design to achieve free motion underwater and imitate the bell kinematics of biomimetic jellyfish [47]. IPMC actuators have attractive features for soft robots, such as large bending deformation. However, the force generated by IPMC is relatively small. Other ionic polymers can also be used in numerous applications in soft underwater robots [48], such as a fish-like micro-robot using ionic conducting polymer [48], a robot fish using a conducting polymer actuator [49, 50], a micro jellyfish [51] using SMA and ionic conducting polymer and a micro conducting polymer actuator that can operate in both air and liquids [52]. All these actuators have the potential to be candidates for micro-electromechanical systems (MEMS) and bio-inspired soft robotics.

Ionic EAPs can also be used in other soft robot applications. A novel biomimetic walking gel was presented in [43], where a synthetic polymer and cyclic reaction network were used as a metabolic procedure to make the gel move by itself. Several investigations on ionic EAPs have also been reported, such as an IPMCs grasper [53], biomedical conjugated polymer actuators [54] and a valve for microfluidic systems using conducting polymer [55]. However, the low force output limits its applications in milli- and micro-domain robotic applications.
Figure 2.4. (a) Polymer gel actuator [43]. (b) Bending motion of IPMC actuator upon applying an electric field [44]. (c) Mechanism of conducting polymer actuator [56]. (d) Self-walking gel [43]. (e) Jellyfish-like ionic polymer-metal composite actuator [45]. (f) Structure of conductive polymer actuator [41]. (g) Biomimetic undulatory tadpole robot using IPMC actuators [44]. (h) Movements of Flemion-based IPMC actuator [53].
2.2.2.2 Electronic electroactive polymers

Electronic EAPs are the insulators that respond to the surface charges, which are usually activated by electrostatic forces. In contrast to ionic EAPs, electronic EAPs can provide higher force and strain. However, they require a high actuation voltage to obtain large deformation and high stress. Electronic EAPs are mainly classified into four categories: electrostrictive polymers, dielectric elastomers (DEs), liquid crystal elastomers and CNT aerogels [41, 42, 57].

![Diagram of electronic electroactive polymers](image1.png)

Figure 2.5. (a). Actuation mechanism of dielectric EAPs [42]. (b). Elastomer artificial muscles [58].

Among these electronic EAPs, DEs are widely used in soft-sensor and actuator applications because of their excellent performance. DE actuators are formed from a DE covered by two layers of the compliant electrode, as shown in Figure 2.5 (a). The different voltages are applied to the actuator, which activates the actuator. It can provide high efficiency, quick response and large power density. Detailed operation principles and fabrication methods of DEs are summarised in [59]. There are various applications employing electronic EAPs for soft actuators, such as a muscle-like linear actuator [60]. However, more research is required to improve the stability of the material and extend the possible motions.

2.2.3 Magnetorheological elastomers

Magnetorheological material is a new branch of smart materials that can generate motion responding to external magnetic change. The phenomenon in which viscoelastic
properties change in response to the alteration of external magnetic fields is called the ‘magnetorheological effect’ [61]. This phenomenon has attracted the attention of researchers to design and fabricate a new generation of soft actuators and dampers. Generally, it consists of magnetorheological (MR) fluids, MR foams and MR elastomers.

Figure 2.6 (a) displays a novel soft actuator that employs both MRE and an electromagnet [62]. The soft actuator consists of an electromagnetic coil, an iron core and silicone elastomer covered by the magnetic elastomer. When a magnetic field is applied, the magnetic elastomer will push the silicone elastomer. After removal of the magnetic force, the MR elastomer will recover to its original position.

A soft MRE with a ring-shaped body as a new actuator for valve applications was presented in [63]. This study concentrated on evaluating the effect of different materials and parameters on the actuation performance of MREs. The researchers characterised the detailed actuation performance of soft MRE materials in magnetic fields of variable properties. They also demonstrated the comparison of anisotropic and isotopic actuation of MRE rings with different Shore hardness. This type of actuator is employed to control airflow.
Several studies have examined the properties and applications of MR fluids, MR foams and MR elastomers [64-67]. MR elastomers are solid, rubber-like materials that have a more uncomplicated control strategy. MREs can provide perspective applications for soft robotics because of their good performance, such as large strain, simple control, pronounced deformation and fast response [62, 63]. However, their applications for soft robotics are minimal.

### 2.2.4 Electrorheological fluids

ERFs are fluids that can respond to the electric field in a concise time (within milliseconds). The properties of ERFs can perform controllable changes through an external electric field. When the electric field is not applied, the flow resistance of the liquid is small. After exposure to the electric field, the crystal molecules rotate to a position with larger flow resistance because of an induced dipole moment, as shown in Figure 2.7 (a). This effect leads to changes in the viscosity, yield stress and other parameters. Thus, this liquid can be controlled by external electric field adjustment. ERFs can change from liquid to a solid-like state with a change in the external electric field. ERFs could provide inspiration for new technology that could be used in soft robotics. Several papers have described the properties of ERFs [68-71].

![Figure 2.7](image)

(a) (b)

Figure 2.7. (a) Mechanism of ER effect [72]. (b). State of ER material without and with an electric field [73].

ERFs can be combined with other actuators to fabricate hybrid actuators, such as a hydraulic actuator using ERFs [74]. The ERF is used as the hydraulic fluid to transfer
the power. With the use of ERF, the actuator can respond very rapidly (about 1.5 ms). This design indicates the possibility for ERF to be used in hybrid soft actuators. A MEMS-based advanced flexible microvalve for soft microactuators using ERF and thin cantilever structure was reported in [72]. The structure of the actuator is shown in Figure 2.8 (a). A microfluidic channel was embedded into the layer with four electrode pads to apply the electric field to the fluid. A wire with loads was attached to the tip of the cantilever to analyse the bending performance. The actuator could be applied as a three-port valve with a drain port (Port A), a supply port (Port B) providing constant pressure and a control port (Port C). This actuator has a wide range of bending angles, as shown in Figure 2.8 (b). Electrorheological gel is also attracting the attention of researchers, and previous studies have presented several actuators based on ERF and electrorheological gel [75-77].

![Figure 2.8. (a) Structure of flexible electrorheological microvalve. (b) Bending state of flexible electrorheological microvalve [72].](image)

The main advantages of ERFs are that they can provide high yield stress and fast response time, have a small size and have low current density. Other types of actuators can also be combined with ERFs, which has inspired engineers and researchers to develop novel hybrid soft actuators. However, the applications of ERFs in soft robotics are very limited because of their complexity, high cost, high voltage required and safety issues. Future work should concentrate on developing ERFs with various properties to satisfy different applications in robotics and other research fields.
2.3 Tendon-driven Soft Actuators

Tendon-driven soft actuators—typically cables or SMA wires driven—are widely used in continuum soft manipulators. Cables or SMA wires are attached to the body of the actuator so that the manipulators can be used without the exoskeleton. For example, a tendon-driven bending actuator using SMA was demonstrated in [78]. The working mechanism of the actuator is shown in Figure 2.9 (a).

![Figure 2.9 (a) Mechanism of tendon-driven actuator with SMA wire [78].](image)

The SMA wire was embedded in the main body of the actuator. The displacement of the SMA wire could be transferred to the deformation of the whole actuator. This actuator based on the SMA wire was used in a soft artificial hand application. A cable-driven actuator design for a three-finger gripper application is demonstrated in Figure 2.9. The
actuator was actuated by a single cable tension, and, when actuated, the actuator could generate bending motion. There are numerous similar designs demonstrated in the literature, such as a moving robot [80], robotic hand and gripper [3, 81-84] and assistive wrist glove [85].

2.4. Flexible Fluidic Actuators

2.4.1 Hydraulic actuators

The hydraulic actuator is a flexible fluidic actuator that has a simple actuation mechanism and can provide various motions. Soft fluidic actuators can be used in various soft robotics applications. A hydraulic actuator belongs to fluidic elastomer actuators. Several studies have shown that a hydraulic actuator can deliver high force and power. Okayasu et al. [86] developed a five degrees of freedom (DOF) hydraulic actuator and used it to handle brain tissue in neurosurgery, as shown in Figure 2.10 (a). The performance—especially safety issues—was tested with an insertion experiment. Both of these applications were actuated by water, with consideration of safety issues.

Recent research reported an autonomous soft-bodied fish using a hydraulic actuation mechanism [87]. A new closed-circuit driving system was used, and the soft fish was capable of swimming in three directions. The fish fin could perform propulsion and yaw movements under hydraulic power, controlled by water circulated inside the internal channels of the fish body. This design offers the possibility for hydraulic power to generate three-dimensional movements in fish-like soft robotics.

Several hydraulic actuators have also been used in medical applications, such as hydraulic forceps used in minimally invasive surgery [88] and an active catheter with multi-segments [89]. Examples of artificial hands employing hydraulic actuation technology are the Karlsruhe hand [90] and hydraulic actuated hands [91]. Hydraulic actuation is a vital driving method used in industrial applications. However, the major disadvantage of hydraulic actuators is the high working pressure (about 30 MPa) [92]. The related safety issues have restricted the use of hydraulic actuators in medical applications.
Figure 2.10. (a) Hydraulic manipulator [86]. (b) Micro hydraulic catheter [89]. (c) Hydraulic autonomous soft robotic fish [87].
2.4.2 Pneumatic actuators

Pneumatic actuators are widely used as an actuating method in robotics and automation. Several studies have shown that pneumatic actuators can provide a remarkable range of movements and can be easily operated. They are cheap and safe during human–robot interaction and can deliver high power densities [93, 94]. When compared with hydraulic actuators, pneumatic actuators have better features, such as convenience and simplicity.

With the development of soft materials, different designs of actuation that use pneumatic networks have been proposed in the research field of soft robotics. Pneumatic actuators can achieve different types of motion, such as bending and extension motions, and have high potential to be employed in soft robotics and medical applications because of their compliance and inherent safety. The main advantage of pneumatic actuators is that they are much lighter than those with electric motors.

2.4.2.1 Pneumatic artificial muscles

Pneumatic artificial muscles (PAMs) are one of the most highly focused SPAs because of their favourable compliance. Generally, a PAM includes a flexible inflatable channel that is operated by compressed gas, and an outside mesh. The driving pressure of PAMs is between 50 and 100 psi. This type of actuator can achieve linear motion. The geometry of a PAM is shown in Figure 2.11.

![Figure 2.11. Geometrical model of PAM during (a) relaxed and (b) inflated state under load][95].
The McKibben artificial muscle is one example of the most frequently used and researched PAMs in robotic applications, and has existed for more than 50 years [96, 97]. The McKibben artificial muscle was invented by McKibben as an orthotic device [96] and successfully used by McKibben in prosthetics [98]. The power source for the actuator is compressed gas. The actuator has an inflatable inner bladder sheathed with two spiral weaves, which causes the actuator to shrink along the lengthwise direction when expanded radially. The PAM is a simplified type of pneumatic actuator. The limitation of the McKibben artificial muscle is that it can only achieve one-dimensional movement.

Several artificial hands using PAM have been presented. For example, ‘Blackfinger’ [99] has five fingers that are actuated by McKibben pneumatic actuators. Each finger has four DOF. A spherical joint is provided by the first phalanx, which can provide two DOF. The cylindrical joints are applied between the adjacent phalanxes. These joints make it possible for the fingers to rotate around the axial. A particular cutting method is used to make the joints replicate human bone shapes and structures. In [100], the researchers described a prosthetic glove driven by rubber PAM. The glove makes it possible for the fingers to generate the effect of bending and grasping. Another pneumatic actuated hand, ‘Shadow Hand’, is driven by forty shadow air muscles. This hand can provide 24 DOF, and has a similar force and sensitivity to a real human hand [101]. A special pneumatic actuator is adapted in this design, which is an actuator similar to the PAM, with a light weight. The speed of the hand is about half the speed of a real hand.

PAMs can provide fast actuation; however, they can provide only one moving mode (contraction and elongation). Thus, this type of pneumatic actuator is not suitable for complex actuation movements.

2.4.2.2 Pneumatic balloon actuators

Generally, pneumatic balloon actuators have many appealing features, such as a light weight and flexibility; thus, they have numerous applications in the micro soft robotics research field. Satoshi Konishi et al. [102] presented a pneumatic balloon actuator (PBA) made of silicone rubber. Its structure was very simple, with two flexible layers
combined and fixed as a cantilever. The upper silicone rubber layer plays the role of a membrane, and the lower polyimide layer acts as a substrate. The two layers are combined along the edge by silicone rubber glue, thus creating a chamber inside. The working principle and motion are shown in Figure 2.12 (a). This actuator can provide large bending deformation and force. Similarly, micro fingers with similar balloon actuators have also been reported [103, 104].

Figure 2.12. (a) Working principle and motion of a PBA [102]. (b) Micro hand using PBA [104]. (c) Longitudinally-divided micro PBA [105]. (d) Three-finger micro hand [106]. (e) Micro finger for cellular aggregate [107].
Some PBAs can perform bending motions in two directions. A new PBA that can provide bidirectional bending movements has been used in a micro manipulation robot application [108]. The bidirectional actuators generally comprise two layers of polydimethylsiloxane (PDMS) elastomer with different thickness. The structure is similar to the unidirectional bending actuators listed above. The actuator moves upwards when a smaller pressure is applied, while, when the pressure inside becomes larger, the actuator moves downwards. Similarly, a longitudinally-divided micro PBA was developed in [105], and a three-finger micro hand using a curling actuator was proposed in [106]. Some other bidirectional actuators were summarised in [109].

Recently, Satoshi Konishi et al. described a pneumatic balloon micro finger for a cellular aggregate of human mesenchymal stem cells [107]. The micro finger was only 12 mm in length, with a 900 μm fingertip. The main applications of PBAs are micro robots and machines because PBA is flexible and has a relatively low weight.

### 2.4.2.3 Pneumatic network actuators

Alongside the development of soft materials, different designs of actuation with various sizes and functions that use pneumatic networks (PneuNets) have been developed in the research field of soft robotics. Figure 2.13 (a) displays an actuation methodology based on PneuNets [94] that can perform complex motion with only one pressure source. The movements of this soft actuator are generated by pressurising the internal PneuNets, and the configuration of the actuator is determined by the structure of the channels. Air was selected as the power source because of its unique features, such as compressible ability, easy storage, low viscosity and rapid actuation process. The same methodology was also used in a multi-gait quadrupedal soft robot, as shown in Figure 2.13 (b) [110], and a camouflage/display soft robot [111]. These robots have no rigid internal skeletons, as with certain animals, such as squid, starfish and worms. The camouflage/display soft robot described in [111] combines microfluidics and PneuNet technology. The PneuNets used for inflation are embedded as the independent lower layer, and the colour-filled microfluidics channels in the thin silicon surface are used as camouflage. Various similar applications using this type of actuator have been described in other research [112-114].
Figure 2.13. (a) PneuNets actuator [94]. (b) Multi-gait quadrupedal soft robot [110]. (c) Camouflage/display soft robot [111]. (d) Soft autonomous actuator [114].

Previous research developed a giant rapidly pneumatically actuated soft robot (0.65 metres in length) with embedded controllers, battery and miniature compressors [115] as shown in Figure 2.14. The sizeable soft robot could carry its power system and adapt to various environments. The main difference between the large robot and PneuNets robots was the small gap between the adjacent channels. The large robot could provide higher strength and rapid movement, while having low density and more stable actuation. Recently, Bobak Mosadegh et al. made some improvements to the pneumatic net actuator and developed a fast PneuNet actuator [93] made of silicone rubber. They compared the slow and fast actuation using PneuNets and showed a novel pattern of actuation that was sufficiently durable. This fast PneuNet actuator could bend into a circle at low inflation rates. This design significantly improved the performance of the pneumatic actuator. Further research developed a hand rehabilitation glove using this fast SPA [116]. They reported the initiatory steps for the design, fabrication and evaluation. The rehabilitation glove was not only safe, but could also be applied to various environmental conditions. Several other studies have reported similar actuation mechanisms that can perform bending movement [117-121]. Various applications that
generate bending motion based on pneumatic actuators have been reported in the literature. Examples of SPAs that generate cyclic and 2D bending motions include hand-assistive and rehabilitation systems [122-127], swimming robots [128], miniature soft hands [129], micro 2D spiral robots [130], walking robots [131], underwater robots [132] and so forth. Such pneumatic actuators can generate bending movements, thereby offering high potential to be employed in soft robotics and medical applications. To expand the applications and accomplish more complex tasks, SPAs that can generate more DOF are required. Studies on the SPAs that can generate 3D movements [133-137] are very limited in soft robotic applications.

Figure 2.14. (a) Large rapidly pneumatically actuated soft robot [115]. (b) Soft and highly compliant 2D robotic manipulator [121].

The useful features of pneumatic actuators have attracted the focus of engineers and researchers from various disciplines. Compressed air can provide rapid inflation and is convenient to obtain, lightweight and very easy to control and measure. As a result of these extraordinary properties, pneumatic actuators are good choices for prosthetic
hands. However, further research is required to clarify the parametric effects on their actuation performance.

Table 2.1. Comparison of various actuators [92, 138].

<table>
<thead>
<tr>
<th>Actuator Type</th>
<th>(\varepsilon_{\text{max}})</th>
<th>(\sigma_{\text{max}})</th>
<th>(\rho[\text{kg/m}^3])</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscle</td>
<td>0.3–0.7</td>
<td>0.0–0.4</td>
<td>1,000–1,100</td>
<td>0.2–0.25</td>
</tr>
<tr>
<td>Pneumatic</td>
<td>0.1–1</td>
<td>0.5–0.9</td>
<td>180–250</td>
<td>0.3–0.4</td>
</tr>
<tr>
<td>Hydraulic</td>
<td>0.1–1</td>
<td>20–70</td>
<td>1,600–2000</td>
<td>0.9–0.98</td>
</tr>
<tr>
<td>SMA</td>
<td>0.007</td>
<td>100–700</td>
<td>6,400–6,600</td>
<td>0.01–0.02</td>
</tr>
<tr>
<td>EAPs</td>
<td>0.5</td>
<td>0.3</td>
<td>1,000–2,500</td>
<td>0.3</td>
</tr>
<tr>
<td>MREs</td>
<td>0.002</td>
<td>10</td>
<td>3,000–4,000</td>
<td>0.8</td>
</tr>
<tr>
<td>ERFs</td>
<td>0.5</td>
<td>0.02</td>
<td>1,000–2,000</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Notes: power density, \(\rho\) = power per unit of weight; \(\sigma_{\text{max}}\) = maximum force exerted by the actuators per area; \(\varepsilon_{\text{max}}\) = maximum run per length. Maximum stress and strain are indexes specifically designed for linear actuators. Units are expressed as follows: W = watt, kg = kilogram, MPa = megapascal, GPa = gigapascal.

Table 2.1 provides detailed information on the possible actuators for soft robots described above. Although SMA actuators are able to generate large displacements, their extremely low efficiency because of energy consumption by wire heating is an issue. Ionic EAPs can operate with very low driving voltages, yet have a slow response speed. In contrast, electronic EAPs respond rapidly, yet require high driving electric fields. MREs and ERFs have a short response time and can be controlled by external energy fields. Hydraulic actuators have relatively high efficiency and can deliver high force and power. However, their high working pressure and safety issues restrict their applications in biomedical fields. Compared with hydraulic actuators, pneumatic actuators are light weight, compliant and inherently safe. Overall, this section has discussed the working principles, advantages and limitations of the above actuators, and compared the properties of different soft actuators, such as maximum strain, maximum stress, density and efficiency. Different types of soft actuators have advantages and drawbacks, and the specific requirements corresponding to various applications should be considered when designing soft actuation systems.
Chapter 2

2.5. Fabrication Method of Soft Actuators

2.5.1 Moulding-based fabrication methods

Moulding is a commonly used manufacturing process that shapes the liquid or pliable raw material into soft structures using a predesigned rigid frame as a mould. This technique is widely used for fabricating various applications with different sizes, materials and functions. Moulding is a popular fabrication technique for elastomer-based soft actuators because of its fast fabrication and low cost.

2.5.1.1 Soft lithography for micro/nanostructures

Soft lithography is based on moulding the elastic model using the pattern of interest in bas-relief. Soft lithography is simply a technique, and it can provide many powerful routes for the manufacture of micro/nanostructures. Soft lithography has many advantages as biotechnology for generating microstructure applications [139, 140]. It is widely used for manufacturing simple micro structures on the surface or in a structure [141, 142]. As a result of its favourable mechanical properties, PDMS is widely used to fabricate micro fluidic structures [143]. Many types of micro/nano-machining technology can be used to create an integrated soft robotic system. Soft lithography provides many features that are better than lithography.

| Table 2.2. Soft lithographic methods for the fabrication of micro/nanopatterns [141]. |
|---------------------------------------|---------------------------------------------|
| **Contact Printing**                  | **Capillary Moulding**                      |
| Mould                                | PDMS                                        |
| Soft mould                           | Rigiflexible mould (PUA)                    |
| PDMS                                 |                                             |
| Hard PDMS (h-PDMS)                   |                                             |
| Application                          | Fabrication of micro/nanostructures (2D structure) |
| Direct printing of biological molecules (1D chemical modification) |                                             |
| Process                              |                                              |
| SAM solution                         | Polymer coating                             |
| PDMS mold                            | Mold placement                              |
| Substrate                            | Heat or UV                                  |
| Substrate                            | Mold removal                                |
Many types of micro/nanofabrication technology can be used to create integrated micro systems. Previous research introduced two types of soft lithographic methods (contact printing and capillary moulding) to create micro/nanopatterns on a surface or within a microfluidic channel [141]. The difference between contact printing and capillary moulding is presented in Table 2.2.

### 2.5.1.2 Micro-moulding for micro/nanostructures

Micro-moulding technique is one of the manufacturing techniques for fabricating micro biological devices. Injection moulding is usually used in industrial mass production of plastics components. As a cheap alternative to the glass-based MEMS technology, fabrication of polymer is becoming increasingly important. Nowadays, in life sciences, MEMS applications are trendy in the biological field [144]. MEMS products use silicone and usually have good surface quality, yet are often expensive and unsuitable for cheap and mass production [145]. Nowadays, many micro-fabrication techniques to fabricate polymer-based materials—such as microinjection moulding and casting—have been used in applications with micro bio-systems.

Polymer-based materials have many advantages in the field of soft robotic research—they provide a wide range of physical and chemical properties and are easy to produce [145]. In previous decades, much research has investigated the moulding process for micro devices. The moulding process is a preferred method because it works rapidly and has advantages in terms of cost and mass production.

### 2.5.1.3 Lost-wax casting for soft robotics

Lost-wax casting, also called *cire perdue*, is a method of duplicating structures through pouring melted materials into moulds made of wax. The wax mould can be melted and removed from the fabricated structures. A SPA and ribbed soft fishtail were fabricated in [146] using lost-wax casting. The fabrication process is demonstrated in Figure 2.15. There are eight steps in total, and Steps A to F are a commonly used moulding process. In this previous study, the difference was that a wax mould was used in this method to form the inner structure.
Figure 2.15. Fabrication process for PneuNet actuator with lost-wax casting combined with moulding [146]: (A) pour the uncured silicone rubber into moulds and cure a rubber mould; (B) pour the wax core with embedded supportive rod into the cured rubber structure; (C) combine the moulds; (D) pour rubber into the assembled mould to create the bottom layer of the actuator; (E) create a constraint layer; (F) remove the silicone actuator from mould; (G) melt out the wax core from the actuator using an oven; and (H) cured actuator structure.

2.5.1.4 Moulding used in soft actuator applications

Figure 2.16. Fabrication process of a soft elastomer fibre-reinforced bending actuator using predesigned mould [147].

Moulding is the most commonly used method in silicone elastomer-based soft actuator applications because of its rapid and efficient characteristics. This approach is used in
various SPA designs, such as fibre-reinforced actuators [148] and PneuNet actuators [110, 149]. The moulding fabrication process of a fibre-reinforced bending actuator is shown in Figure 2.16 [147]. The silicone rubber was poured into pre-prepared moulds to create a half round soft cylinder. A limited strain layer and fibre reinforcement were then added. Another thin rubber layer was attached to the outside surface of the actuator using a new set of moulds. A similar technique is also a popular method for fabricating assistance and rehabilitation applications [127]. A PneuFlex actuator used in prosthetic and rehabilitation devices is shown in Figure 2.17. The actuator has three fingers, made of reinforced silicone rubber and actuated pneumatically. The PneuFlex finger consists of two layers. The bottom layer is a passive layer, and the other apparent layer on the top is the active layer. The silicone tube, formed by the two layers, is filled with air. Another tube is inserted into the finger at one end to press air into the chamber, as shown in Figure 2.17 (d). Similar graspers using a PneuFlex actuator are reported in [150]. A similar technique was used to fabricate a bending pneumatic elastomer soft actuator designed for a soft-bodied swimming robot inspired by manta fish [128].

![Image](image.png)

Figure 2.17. RBO Hand and PneuFlex actuator [151].

During recent decades, a variety of elastomer-based soft PneuNet actuators have been described in the literature. The method was first demonstrated to be used for designing a multi-gait soft robot [110] and a soft gripper [149]. A soft pneumatic edible soft actuator made of a gelatine-glycerol composite was fabricated based on moulding technique [152]. This design offers the possibility to fabricate a new type of edible soft
robots. A similar approach has also been used in a bidirectional elastomer actuator [153].

Moulding is widely used because of its low cost and ease of use. However, moulding also has some limitations, such as resolution, the selection of materials and the complicated mould design and fabrication process. To fabricate more complicated structures with various functions, the mould design presents a critical problem. Recently, 3D printing has provided a novel method to fabricate moulds. With the development of 3D printing, more SPAs with different functions have been demonstrated.

2.5.2 3D printing technology

In contrast to conventional fabrication methods, 3D printing is a novel, rapid fabrication technology that is suitable for creating a complicated design without post-processing, especially for designs with inner structures. The marginal cost of design iteration and fabrication can be reduced significantly through additive manufacturing methods. Developing soft robotic applications, especially for actuators and sensors, by means of 3D printing is an emerging research topic. In past decades, 3D printing has been an emerging technology to fabricate soft robotics, and numerous fabrication techniques based on 3D printing (additive manufacturing) have been reported to create various soft robots with different applications.

As a typical conventional fabrication method, moulding was widely used in the fabrication process of soft robots prior to the development of 3D printing technology. However, there are several issues related to this process, such as high cost, complicated procedures and limited machining resolution, which have confined its application in complex and high-quality soft robots. In contrast, 3D printing is a novel fabrication method that has become widely used in various soft robotics applications, ranging from 3D printable soft sensors [154] and soft actuators to some soft structures for soft robots. In recent decades, there have been a variety of 3D-printed soft robotic applications described in the literature, several examples of which are shown in Figure 2.18.
Figure 2.18. (a) Schematic of 3D stereolithographic printer and the fabrication process of ‘bio-bots’ [155]. (b) Embedded 3D printing process and the fabricated strain sensor [156]. (c) A fully soft and autonomous octobot [157]. (d) Multi-material, 3D-printed, graded soft robot powered by combustion [158].
Additive manufacturing methods not only reduce the cost of fabrication, but also enable fabrication of highly complex geometries within the topology of a soft robotic device. In the early stage of 3D printing, the stiffness of 3D-printed structures was limited by the material properties, such as rigid plastics, and the 3D printing method was generally used to fabricate hard moulds for soft pneumatic and hydraulic actuators [93, 124, 131, 149, 159-161]. However, direct 3D printing helps broaden its applications in soft actuator research.

A multi-material locomotive ‘bio-bot’ was developed using a 3D stereolithographic printer, where the two vital components—cantilever and base—were fabricated layer by layer, as shown in Figure 2.18 (a). First, a pattern of the cantilevers was traced onto the surface of a thin layer of poly (ethylene glycol) diacrylate (PEGDA) hydrogel precursor solution with an ultraviolet (UV) laser beam with 325 nm wavelength. The part was then recoated with a thin layer of PEGDA hydrogel precursor solution, and the laser traced a pattern of the bases. By means of 3D printing technology, a precise and iterative design of bio actuators was achieved [155]. Joseph T. Muth et al. [156] reported an embedded 3D printing of a carbon-based resistive ink within an elastomeric matrix. By adjusting the print path and filament cross-section in the 3D printing process, the geometry and properties of the sensor could be adjusted, which offers promising applications for various soft functional devices. Similar embedded 3D printing has also been combined with the micro-moulding technique to rapidly create entirely soft, autonomous octopus-like robots, as shown in Figure 2.18 (c) [157]. A 3D-printed functionally graded soft robot powered by combustion was reported by Nicholas W. Barlett et al. [158]. The multi-material 3D printing allows for greater freedom and enables rapid design iteration with no additional cost.

Based on the operation mechanism, 3D additive manufacturing technology can be divided into two types—light-based and ink-based 3D printing—providing new methods for fabricating soft robotics with complex structures [162]. There are also several sub-classifications for each type of 3D printing method, as shown in Table 2.3. The working mechanisms of different 3D printing techniques, as well as the related applications for soft actuators, will be introduced in the following sections.
Table 2.3. Additive manufacturing methods for soft robotics applications.

<table>
<thead>
<tr>
<th>3D Printing Technique</th>
<th>Application</th>
<th>Action</th>
<th>Material</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light-based 3D printing</td>
<td>Stereolithography</td>
<td>Artificial muscle</td>
<td>Pneumatic</td>
<td>Photopolymer isable elastomeric material [163]</td>
</tr>
<tr>
<td></td>
<td>Micro-bellows actuator</td>
<td>Bellow actuator</td>
<td>Photopolymer</td>
<td>[164]</td>
</tr>
<tr>
<td></td>
<td>Inflatable structures</td>
<td>Pneumatic</td>
<td></td>
<td>[165]</td>
</tr>
<tr>
<td>Selective laser sintering</td>
<td>Robotic hand</td>
<td>Bellow actuator</td>
<td>Flexible polyurethane</td>
<td>[166]</td>
</tr>
<tr>
<td></td>
<td>Robotic hand</td>
<td>Pneumatic</td>
<td>Highly stretchable and UV-curable (SUV) elastomers</td>
<td>[167]</td>
</tr>
<tr>
<td>Digital light processing</td>
<td>Gripper</td>
<td>Pneumatic</td>
<td></td>
<td>[1]</td>
</tr>
<tr>
<td></td>
<td>Pipeline</td>
<td>Photopolymer isable resins</td>
<td></td>
<td>[168]</td>
</tr>
<tr>
<td></td>
<td>Soft robot generating inching and crawling locomotion</td>
<td>SMA</td>
<td>Soft rubber-like object and hard polypropylene-like object</td>
<td>[169], [170]</td>
</tr>
<tr>
<td>Inkjet printing</td>
<td>Direct ink writing</td>
<td>Botanical-inspired composite architectures</td>
<td>Smart materials</td>
<td>Hydrogel [171]</td>
</tr>
<tr>
<td></td>
<td>Artificial meniscus</td>
<td>Hydrogel</td>
<td></td>
<td>[172]</td>
</tr>
</tbody>
</table>
2.5.2.1 Light-based 3D printing

Light-based 3D printing techniques—such as stereolithography [155, 163, 179], selective laser sintering [166, 180], digital light processing [1], digital projection lithography [181] and photo-curable inkjet printing [20, 155, 182]—employ light to create complex 3D geometries.

A. Stereolithography

Stereolithography is one typical light-based 3D printing technique that adopts the photochemical processes by employing light to cause chemical monomers to link together, layer by layer, to form a 3D solid. Byran N. Peele et al. used an automated stereolithography technique to fabricate SPAs with complex internal structures, as this technique can provide high resolutions rapidly without the assistance of additional support material. A bottom-up digital mask projection stereolithography system has
been developed, which consists of a digital mirror device, a light source, a focusing lens, photopolymer resin and the build platform, as shown in Figure 2.19 (a). The digital mirror device is used to illuminate and photopolymerise an entire layer at once, and the high-definition projector can provide a resolution of 37 µm in the horizontal plane. Based on the bottom-up process, the pattern from the projector can pass through the transparent build tray, and finally be projected into the photopolymer resin. The SPA printed in the process is shown in Figure 2.19 (b). Stereolithography can also be applied to fabricate high-resolution micro structures with shape-memory polymers [183].
Figure 2.19. (a) Diagram of bottom-up digital mask projection stereolithography (DMP-SL) system. (b) SPA printed by DMP-SL system. (c) SUV elastomers for digital light processing–based 3D printing [1]. (d) Schematic of inkjet printing [2]. (e) Actuated robotic finger fabricated via fibre embedding in a PolyJet 3D printing process [2]. (f) 3D printed flexure hinges for soft monolithic prosthetic fingers [3].
B. Selective laser sintering

Selective laser sintering is another light-based 3D printing method, where a laser is used to act as the energy source to sinter the powdered target materials. Previous research created a soft robotic hand consisting of four fingers and 12 DOF using bellows actuators, and used quick valves to pressurise the actuators. Various soft actuators have been reported to be created by selective laser sintering technique [167].

C. Digital light processing

Another light-based additive manufacturing technique with low cost is digital light processing. Digital light processing is an ideal method to produce porous structures and various structures with trusses or cavities [158, 184], as the printing process occurs in a liquid bath and no support material is required. Figure 2.19 (c) shows SPAs printed by digital light processing technique. SUV elastomers have been reported as suitable for the digital light processing technique, with fast printing speed and high resolution [1]. Both digital light processing and the stereolithography method belong to vat polymerisation, as the photopolymer resin and light source are the two components in the printing system. The main difference between these two methods is the type of light source. In the stereolithography process, a laser is usually used as the light source to cure the resin. In contrast, a digital light projector screen acts as the light source in the digital light processing method, which makes it more efficient for creating complex 3D structures with multi-scales ranging from microscale to mesoscale.

D. Inkjet printing

Figure 2.19 (d) shows the typical inkjet printing process [2]. Given that multiple inkjet printing heads can be installed into the inkjet printing system, various materials with different optical and mechanical characteristics can be loaded into the printing heads and deposited to the same layer, which makes it a feasible method to fabricate multi-material targets and graded structures with embedded components, without disturbing the previously printed layer [168]. However, the deposited support material must be removed manually from the void for the embedded components.
2.5.2.2 Ink-based 3D printing

Light-based 3D printers offer the possibility to print soft structures with high resolution; however, this method is limited by the printing materials. Ink-based 3D printing techniques are only suitable to pattern photopolymerisable resins, such as thermoset polymers and thermoplastic polymer powders, which may limit their application in the soft robotics field. Ink-based 3D printing—such as direct ink writing [154, 171, 172, 185, 186], shape deposition modelling [174, 187, 188] and FDM [189]—is another popularly used method in soft robotics research that can be used to fabricate complex structures with a wide variety of soft materials. In all these widely used additive manufacturing methods, the printing material—such as polymers, smart materials, resins, fluids, filaments and hydrogels—change from a mobile state (or a mobile state after melting) to a solid state. Several typical ink-based 3D printing techniques are introduced below.

A. Direct ink writing

The typical technique of ink-based 3D printing methods is direct ink writing, which creates various 3D objects layer by layer through direct deposition of liquid ink to the target printing stage. Daniel Therriault et al. [190] fabricated 16-layer scaffolds with the direct ink writing method. An ink delivery system was mounted on the z-axis with a cylindrical nozzle, and the volumetric flow rate was controlled to maintain a constant deposition speed of 15 mm/s. One of the most important steps in the direct ink writing process is adjusting the viscoelastic properties of the ink, which should simultaneously permit flow while facilitating shape retention of the as-deposited filament, even as it spans gaps in the underlying layer(s). In Therriault et al.’s study, this deposition process was repeated as the movement of the stage in the z-axis until the 3D scaffold had been achieved. Similar 3D micro periodic structures were also directly written by G. M. Gratson et al. [191] using concentrated polyelectrolyte inks.

B. Shape deposition modelling

The shape deposition modelling method allows for embedded components, such as actuators and sensors. Compared with the conventional additive manufacturing methods, the shape deposition modelling technique permits more freedom to access the internal geometry of the structures, where actuators, sensors and pre-fabricated
functional components can be embedded into the structures. In addition, the properties of the final part can be adjusted by controlling the deposition materials in different layer deposition stages. By using shape deposition modelling technique, multi-material, embedded heterogeneous structures can be created, which can be used for advanced tooling and embedded electronic devices [192].

C. Fused deposition modelling
Among the additive manufacturing techniques, the FDM technique has been demonstrated to be the most widely used method to rapidly fabricate various complex 3D structures at a low cost. Several types of thermoplastic polymer can be used to fabricate 3D structures, including acrylonitrile butadiene styrene (ABS), polylactic acid (PLA) and polycarbonate. Special particles, such as carbon black, can be filled into the polymer filaments to enhance the functionality of the printed parts. As a result of its low cost, reduced time, simple processes and broad range of filament materials, FDM has been widely used in the soft robotics field. Rahim Mutlu et al. [3] used FDM to fabricate flexure hinges and soft monolithic robotic fingers, as shown in Figure 2.19 (f). A monolithic soft gripper with adjustable stiffness has also been developed and fabricated through the 3D printing based on the FDM method, with an average wall thickness of 0.58 mm. FDM can be used to create diverse soft actuators with multi-functions for application in the bio and medical fields.

2.6. Conclusions
Soft robots offer flexibility and high compliance during interactions with their immediate environment, including with humans; thus, they can generate multi-DOF movements for many applications. In this chapter, the fundamental mechanisms of actuators, including the actuation and fabrication methods, have been reviewed to provide an essential understanding of soft actuators. Three types of actuation mechanisms have been discussed—soft actuators made of smart materials, tendon-driven actuators and flexible fluidic actuators—both in theory and application. Different approaches have been proposed to explore the actuation concepts, including experimental and analytical studies, as well as computational methods. However, further research is necessary to gain an in-depth understanding of the soft pneumatic actuation mechanisms and their applications. Fabrication of SPAs has attracted much
research interest for various soft robotic applications, and different methods have been proposed. Of these, 3D printing has gained significant attention for soft robotics. Further efforts are required to attain a better understanding of the printing process for printing many non-metallic and metallic materials. Overall, based on this literature review, PneuNet actuators appear to be a practical choice for soft robotic applications.
Chapter 3

Mechanical Properties and Finite Element Modelling of Hyperelastic Materials for Soft Robotic Applications

3.1. Introduction

The field of soft robotics aims to establish robotic systems primarily made of soft materials \( (E < 100 \text{ MPa}) \) to perform complicated locomotion in various environments and interact with and adapt to their physical environments in a safer and more successful manner than their predecessors (conventional robotic systems made of hard materials), without requiring advanced feedback control techniques. Hyperelastic materials with high flexibility and large strain are widely used in soft robotic applications for various purposes, such as flexible actuators [93, 94, 159, 193-196] and soft stretchable sensors [156, 197-201].

Hyperelastic materials are nonlinear materials that can generate a large deformation under a relatively low force. These materials include elastomers, silicone rubbers and rubber-like materials. Hyperelastic materials have several specific properties that make them a popular choice for soft robotics, as follows [202]:

- they are fully recoverable with large deformation (normally 100 to 800\%), which means they can restore their initial configuration after a large elastic deformation

- they are soft and nearly incompressible, which makes them retain their overall volume when their configuration has been changed under large loads.

The mechanical behaviour of these materials is complex, such that their stress–strain relationship is derivable from a strain energy function. In the last few years, many strain energy function models have been proposed to evaluate the elastic behaviour of these materials, using tensile test experimental data [202]. Hyperelastic strain energy models are used to represent their large deformation behaviour in FEM. A variety of strain energy models have been developed in the literature, such as the Gent and Thomas model [203], Hart-Smith model [204], Valanis and Landel assumption [205], three-
chain model [206], constrained-junctions model [207], Arruda-Boyce [208] model, Blatz-Ko model [209], neo-Hookean model [210], Moony-Rivlin model [211-213], polynomial model, Gent model [214], Yeoh model [215-217] and Ogden model [218]. These models are based on principal stretches and strain invariants. Isotropic models are characterised by strain–stress energy behaviours and continuum mechanics. The Arruda-Boyce and Blatz-Ko models are two forms of isotropic hyperelasticity materials, which are used to simulate some of the incompressible or nearly incompressible hyperelastic materials. The isotropic models are physically hyperelastic models, which provide a method to formulate the material response at molecular scale. Extended-tube models—including the neo-Hookean, Moony-Rivlin, polynomial, Yeoh and Ogden models—are widely used to describe rubber-like materials. However, not all models can describe the complete behaviour of different hyperelastic materials, and the selection of an appropriate model depends on its potential applications. Several studies evaluated and compared the ability of these models to represent the complete behaviour of hyperelasticity. Twenty different models were compared and classified into phenomenological models, physical-based models and empirical models in [202].

In FEM, materials are usually defined with Young’s modulus and the Poisson ratio. The Young’s moduli (elastic moduli) of the materials used in this thesis were not provided by the manufacturers and thus were determined by experiments and simulations. As a result of the highly nonlinear behaviour of the materials, it was essential to test and simulate the characterisation of hyperelasticity through FEM. The material constants defined by stress–strain curve fitting in finite element software can be used to simulate various structures and applications fabricated with hyperelastic materials. The ANSYS package provides a variety of accurate strain energy functions to characterise nonlinear materials.

This chapter aims to characterise hyperelastic materials and determine a suitable strain energy function for four soft materials to be used in soft robotic applications. This chapter presents a comprehensive comparison of seven general hyperplastic models describing the material stress–strain behaviour. The abilities of these models are analysed through experimental uniaxial tensile data. The material constants for the four hyperelastic materials can be used in FEM. This chapter theoretically and experimentally studies the mechanical behaviours of silicone rubber (ELASTOSIL
M4061, Ecoflex 00-10, and soft translucent silicones) and thermoplastic elastomer (FilaFlex). The strain and stress data are obtained experimentally using a tensile test machine. In this study, several widely referenced hyperelastic strain energy models—neo-Hookean, Arruda-Boyce, Yeoh, Mooney-Rivlin and Ogden models—are employed in the curve fitting process. This study shows that the Mooney-Rivlin model performs better than the other available models in ANSYS for the four studied materials because of its ability to better match the experimental stress–strain data.

3.2 Experimental Test and Measurement Results

This section tests the stress–strain data of the materials used in this thesis to evaluate the material properties for modelling in ANSYS. To determine the material properties for use in finite element modelling, this study performed uniaxial tensile tests. The tensile tests were conducted according to ISO 37 standard. The stress–strain behaviours of ELASTOSIL M4061, soft translucent silicones, Ecoflex 00-10 and FilaFlex were determined using a tensile tester. 3D additive manufacturing method was used to fabricate the test samples.

3.2.1 Material selection

To fabricate soft actuators, this thesis used three silicone rubbers: Ecoflex 00-10 with a Shore hardness of 10A, ELASTOSIL M4601 with a bulk modulus of elasticity of 262 kPa, and translucent soft with a bulk modulus of elasticity of 48 kPa (experimentally determined [219]). M4601 and translucent soft silicone were used in the soft actuator applications presented in Chapter 4. Ecoflex 00-10 was used in a soft sensor [220] in our research group, and FilaFlex was used in the fabrication of a helical structure, which is introduced in Chapter 5. The material selected for a soft actuator should have a reasonable stiffness to provide a sufficient bending angle and blocking force to perform grasping tasks for soft robotic applications. Silicone rubber was selected as the actuator material because of its low viscosity and relatively high strain rate. This material is inexpensive, can be moulded into a variety of shapes and exhibits properties desirable for the actuator. Tables 3.1 to 3.4 present the datasheets of the selected materials.
Table 3.1. Material ELASTOSIL M 4601—Barnes A/B technical datasheet [221].

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Colour</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density at 23°C</td>
<td></td>
<td>g/cm³</td>
<td>1.14</td>
</tr>
<tr>
<td>Viscosity at 23°C after stirring</td>
<td>ISO 3219</td>
<td>mPa s</td>
<td>15,000</td>
</tr>
<tr>
<td>Mixing ratio</td>
<td>A:B</td>
<td>pbw</td>
<td>9:1</td>
</tr>
<tr>
<td>Viscosity at 23°C</td>
<td>ISO 3219</td>
<td>mPa s</td>
<td>10,000</td>
</tr>
<tr>
<td>Pot time, tack-free</td>
<td></td>
<td>h</td>
<td>12</td>
</tr>
<tr>
<td>Colour</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density at 23°C in water</td>
<td>ISO 2781</td>
<td>g/cm³</td>
<td>1.13</td>
</tr>
<tr>
<td>Hardness Shore A</td>
<td>ISO 868</td>
<td></td>
<td>28</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>ISO 37</td>
<td>N/mm²</td>
<td>6.5</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>ISO 37</td>
<td>%</td>
<td>700</td>
</tr>
<tr>
<td>Tear strength</td>
<td>ASTM D 624 B</td>
<td>N/mm</td>
<td>&gt; 30</td>
</tr>
<tr>
<td>Linear shrinkage</td>
<td></td>
<td>%</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Coefficient of linear expansion</td>
<td>0–150°C</td>
<td>m/m K</td>
<td>$2.4 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Table 3.2. Material datasheet for soft translucent silicone [222].

<table>
<thead>
<tr>
<th>Properties</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colour</td>
<td>Clear/transparent</td>
<td></td>
</tr>
<tr>
<td>Mix ratio</td>
<td></td>
<td>1:1</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>g/cc</td>
<td>1.04</td>
</tr>
<tr>
<td>Hardness</td>
<td>Shore A</td>
<td>0–10</td>
</tr>
<tr>
<td>Pot life</td>
<td>min</td>
<td>30</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>psi</td>
<td>120</td>
</tr>
<tr>
<td>Elongation</td>
<td>%</td>
<td>800</td>
</tr>
<tr>
<td>Tear strength</td>
<td>Pli</td>
<td>22</td>
</tr>
</tbody>
</table>
Table 3.3. Datasheet for silicone rubber Ecoflex 00-10.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colour</td>
<td></td>
<td>Clear/transparent</td>
</tr>
<tr>
<td>Mix ratio</td>
<td></td>
<td>10:1</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>gm/cc</td>
<td>1.08</td>
</tr>
<tr>
<td>Hardness</td>
<td>Shore A</td>
<td>10</td>
</tr>
<tr>
<td>Pot life</td>
<td>min</td>
<td>45</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>Psi</td>
<td>400</td>
</tr>
<tr>
<td>Elongation</td>
<td>%</td>
<td>600</td>
</tr>
<tr>
<td>Tear strength</td>
<td>N/mm²</td>
<td>50</td>
</tr>
<tr>
<td>Demould time at 25°C</td>
<td>Hrs</td>
<td>12–24</td>
</tr>
</tbody>
</table>

Given that it has high elasticity and excellent abrasion resistance, FilaFlex (Recreus Industries SL)—a commercially available TPE with a Shore hardness of 82A—was selected as the filament used in the 3D printing in this thesis. FilaFlex is a 3D-printable, stretchable, soft TPE. It exhibits enough flexibility to fabricate the 3D-printed, all-in-one soft helical actuator and has a lower elastic modulus than several commercially available TPE filaments.

Table 3.4. Datasheet for 3D-printable material FilaFlex.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shore hardness</td>
<td>Shore A</td>
<td>82</td>
</tr>
<tr>
<td>Ultimate tensile strength</td>
<td>Mpa</td>
<td>54</td>
</tr>
<tr>
<td>Elongation to break (ISO 37)</td>
<td>%</td>
<td>665</td>
</tr>
<tr>
<td>Compression set</td>
<td>%</td>
<td>25</td>
</tr>
<tr>
<td>Impact resilience</td>
<td>%</td>
<td>42</td>
</tr>
<tr>
<td>Abrasion resistance</td>
<td>mm³</td>
<td>30</td>
</tr>
<tr>
<td>Density</td>
<td>Kg/m³</td>
<td>1,200</td>
</tr>
<tr>
<td>Extrusion-melt temperature</td>
<td>ºC</td>
<td>200–260</td>
</tr>
</tbody>
</table>

3.2.2 Manufacturing of test samples

The samples of ELASTOSIL M4601, soft translucent silicones and Ecoflex 00-10 were prepared with a pre-fabricated 3D-printed mould and a dog-bone stencil cutter with
dimensions of 10 mm in length and 2 mm in width, as shown in Figure 3.1. The test sample of FilaFlex was prepared as a dog-bone structure and manufactured directly by 3D printing.

### 3.2.2.1 Fabrication of silicone rubber specimens

![Image](image1.png)

**Figure 3.1.** (a) Sample for tensile tests. (b) UP Plus 2 FDM printer. (c) Experimental setup as part of a tensile test machine. (d) Creator Pro, FlashForge 3D printer. (e) Schematic of 3D additive manufacturing process.

The test samples were moulded using the pre-fabricated mould. The detailed fabrication steps are as follows. (i) Prepare two silicone rubbers, mix them with a certain ratio (as explained in the datasheet) and pour them into pre-printed moulds. (ii) Mix the two parts thoroughly and place the mould and mixture into a vacuum machine to reduce the
air bubbles in the material. (iii) Wait for the material to cure at a specific temperature. (iv) Remove the specimens from the mould for testing. This study produced five samples for each elastomer to determine the average Young’s modulus and material constants in finite element curve fitting.

The dog-bone mould for fabricating silicone rubber was fabricated using the UP Plus 2 FDM printer with a resolution of 0.15 mm, as shown in Figure 3.1 (b). The plastic filament used was ABS plastic, which is strong and less prone to warping than other similar materials. It is also chemically reactive to acetone, which can be used to improve the surface finish or remove unwanted parts.

3.2.2.2 Fabrication of thermoplastic elastomer (FilaFlex)

In this study, an FDM printer (Creator Pro, FlashForge) was used to directly manufacture the SPAs, as discussed in Chapter 5. The printer can extrude ABS, PLA, polyvinyl alcohol, high-impact polystyrene, nylon and so forth, with a printing volume of $228 \times 148 \times 150 \text{ mm}$ with 0.1 to 0.3 mm resolution. To create an airtight structure, the printing settings and extruding unit were modified and optimised carefully. Several testing samples were fabricated to optimise the printing parameters. An open-source slicing software (Slic3r) was used to optimise the printing settings. After several tests, the diameter of the nozzle was set to 0.4 mm, and the primary layer height was set to 0.1 mm, with the default printing speed set to 600 mm/min to print an airtight chamber. The printing temperature for FilaFlex should be between 225 and 235°C. After optimisation, the temperature of the nozzle was set to 235°C to provide sufficient adhesion between printing layers. To make the first layer adhere to the platform, the build platform was heated to 35°C. The optimised printing settings were used to fabricate the dog-bone specimens and to print an airtight helical soft actuator with a wall thickness of 0.64 mm, as described in Chapter 5. The specific printing parameters for this method are summarised in Table 3.5.
3.2.3 Tensile test results

The stress–strain performance of the ELASTOSIL M4061, soft translucent silicones, Ecoflex 00-10 and FilaFlex were determined using a tensile tester. The stress–strain data of these hyperelastic materials were determined using tensile tests (Instron tensile machine). A pull-to-failure test was performed at a constant rate for each specimen. More than five samples were prepared to find the average stress–strain value to be used in the modelling. The stress–strain curves for the materials above are presented in Figure 3.2. Three types of dumb-bell-shaped test samples for Filaflex were printed to determine the influence of anisotropic material properties. Three types of samples were printed with longitudinal, crosswise and triangular infills separately as shown in Figure 3.2 (e). The averaged stress-strain relationship obtained for each type was quite similar as shown in Figure 3.2 (d). The results showed that the effect of infill direction on the material properties may be negligible. The stress–strain relationship is nonlinear, as shown in Figure 3.2, and the curve fitting was used to determine the parameters.

### Table 3.5. Optimised printer settings to print FilaFlex.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer</td>
<td></td>
</tr>
<tr>
<td>Primary layer height (mm)</td>
<td>0.1</td>
</tr>
<tr>
<td>First layer height (mm)</td>
<td>0.09</td>
</tr>
<tr>
<td>First layer width (mm)</td>
<td>0.1</td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
</tr>
<tr>
<td>Extruder temperature (°C)</td>
<td>230</td>
</tr>
<tr>
<td>Heated build platform temperature (°C)</td>
<td>35</td>
</tr>
<tr>
<td>Cooling</td>
<td></td>
</tr>
<tr>
<td>Fan speed (%)</td>
<td>60</td>
</tr>
<tr>
<td>Infill</td>
<td></td>
</tr>
<tr>
<td>Interior fill percentage (%)</td>
<td>100</td>
</tr>
<tr>
<td>Outline overlap (%)</td>
<td>20</td>
</tr>
<tr>
<td>Infill extrusion width (%)</td>
<td>100</td>
</tr>
<tr>
<td>Speed</td>
<td></td>
</tr>
<tr>
<td>Default printing speed (mm/min)</td>
<td>600</td>
</tr>
<tr>
<td>Outline printing speed (mm/min)</td>
<td>480</td>
</tr>
<tr>
<td>Solid infill speed (mm/min)</td>
<td>480</td>
</tr>
<tr>
<td>First layer speed (mm/min)</td>
<td>180</td>
</tr>
<tr>
<td>Machine extruider</td>
<td></td>
</tr>
<tr>
<td>Nozzle diameter (mm)</td>
<td>0.4</td>
</tr>
</tbody>
</table>
The samples were stretched at a rate of 100 mm/min using a force transducer. The average data were fitted into several hyperelastic models (Mooney-Rivlin, Ogden, Yeoh and polynomial models) with ANSYS Workbench (release 18.1, ANSYS Inc.).

Figure 3.2. Strain–stress test results for (a) soft translucent silicones, (b) M4601, (c) Ecoflex 00-10 and (d) FilaFlex, (e) Dumb-bell-shaped test samples printed with longitudinal, crosswise and triangular infills.
3.3 Hyperelastic Strain Energy Function Models

There are two types of hyperelastic material models available in ANSYS—isotropic hyperelasticity and extended-tube models—which include:

1. Arruda-Boyce model
2. Blatz-Ko model
3. neo-Hookean model
4. Mooney-Rivlin model
5. polynomial model
6. Yeoh model
7. Ogden model

All these models are pre-programmed in ANSYS, and all can be used to obtain the material constants, using experimental stress–strain data. Each of the hyperplastic models is defined with different strain energy models. A short review of several widely used hyperelastic models is presented next.

3.3.1 Mooney-Rivlin model

To describe the material behaviour, Mooney-Rivlin model [211-213] as a function of strain invariants with two, three, five or nine parameters model can be used and the suitable model can be selected depending on the type of stress–strain curve, as shown in Figure 3.3.

This is one of the most popular models to calculate the material constants of a hyperelastic material through curve fitting. This model is given by:

\[ W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + \frac{1}{d}(J - 1)^2 \]  \hspace{1cm} (3.1)

where \( W \) is the strain energy per unit reference volume, \( I_1 \) and \( I_2 \) are the first and second deviatoric strain invariants, and \( C_{10} \) and \( C_{01} \) are material constants characterising the deviatoric deformation of the material.
The three-parameter Mooney-Rivlin model, which is the default model, has the following form of strain energy potential:

\[ W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + C_{11}(I_1 - 3)(I_2 - 3) + \frac{1}{d}(J - 1)^2 \]  

(3.2)

The five-parameter Mooney-Rivlin has the following form of strain energy potential:

\[ W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + C_{20}(I_1 - 3)^2 + C_{11}(I_1 - 3)(I_2 - 3) + C_{02}(I_2 - 3)^2 + \frac{1}{d}(J - 1)^2 \]  

(3.3)

The nine-parameter Mooney-Rivlin has the following form of strain energy potential:

\[ W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + C_{20}(I_1 - 3)^2 + C_{11}(I_1 - 3)(I_2 - 3) + C_{02}(I_2 - 3)^2 + C_{30}(I_1 - 3)^3 + C_{21}(I_1 - 3)^2(I_2 - 3) + C_{12}(I_2 - 3)(I_2 - 3)^2 + C_{03}(I_2 - 3)^3 + \frac{1}{d}(J - 1)^2 \]  

(3.4)

Figure 3.3. Types of Mooney-Rivlin models [223]: (a) stress–strain curve with single curvature (two-/three-parameter model); (b) stress–strain curve with one inflection point (three- or five-parameter model); (c) stress–strain curve with two inflection points (five or nine-parameter model).
3.3.2 Neo-Hookean model

The neo-Hookean model can be used to fit into nonlinear materials with large deformation. The model was proposed in 1948 by Rivlin [210], and is a particular case of the Mooney-Rivlin model with the material constant $C_{01}$ set as zero. This model is suitable for materials that only generate small strains. The strain energy function is given as:

$$W = \frac{\mu}{2}(I_1 - 3) + \frac{1}{d}(J - 1)^2$$  \hspace{1cm} (3.5)

where $\mu$ is the initial shear modulus of the material, $d$ is the material incompressibility parameter and $J$ is the determinant of the elastic deformation gradient.

3.3.3 Polynomial model

The polynomial hyperelastic material model is a phenomenological model of rubber elasticity. The model is usually used to evaluate the behaviour of filled elastomers [224]. The strain energy function is given by:

$$W = \sum_{i+j=1}^{N} C_{ij} (I_1 - 3)^i(I_2 - 3)^j + \sum_{k=1}^{N} \frac{1}{d_k}(J - 1)^{2k}$$  \hspace{1cm} (3.6)

where $N$, $C_{ij}$ and $d_k$ are material constants.

3.3.4 Blatz-Ko model

Blatz and Ko proposed a compressible model based on a combination of theoretical arguments and experimental work, with the strain energy function, $W$, in the form [209]:

$$W = \frac{\mu}{2}\left(\frac{l_3^2}{l_3} + 2\sqrt{l_3} - 5\right)$$  \hspace{1cm} (3.7)

This nonlinear hyperelastic model is suitable for foam-material in finite strain analysis.

3.3.5 Arruda-Boyce model

Arruda-Boyce is a physically incompressible model—also called an eight-chain model—that was developed based on evaluation of a cubic volume element with eight
chains. The strain energy density function for the incompressible Arruda-Boyce model is given by:

\[
W = \mu \left[ \frac{1}{2} (I_1 - 3) + \frac{1}{20 \lambda_L^2} (I_1^2 - 9) + \frac{11}{1050 \lambda_L^4} (I_1^3 - 27) + \frac{19}{7000 \lambda_L^6} (I_1^4 - 81) + \frac{519}{673750 \lambda_L^8} (I_1^5 - 243) \right] + \frac{1}{d} \left( \frac{J^2 - 1}{2} - \ln J \right) \tag{3.8}
\]

where \( \lambda_L \) is the limiting network stretch, \( \mu \) is the initial shear modulus of the material, \( d \) is the material incompressibility parameter and \( J \) is the determinant of the elastic deformation gradient.

3.3.6. Yeoh model

The Yeoh model developed by Yeoh in 1990 [215] is based on the first strain invariant [225]. It is a phenomenological model for nearly incompressible and nonlinear elastic materials. The strain energy function is:

\[
W = \sum_{i=1}^{N} c_{i0} (I_1 - 3)^i + \sum_{k=1}^{N} \frac{1}{d_k} (J - 1)^{2k} \tag{3.9}
\]

3.3.7. Ogden model

The Ogden material model was developed in 1972 by Raymond Ogden [218]. This model is suitable to describe the non-linear stress-strain behaviour of materials with complex properties, such as rubbers, polymers, and biological tissue, in finite strain analysis. The strain energy function is given by:

\[
W = \sum_{i=1}^{N} \frac{\mu_i}{\alpha_i^2} \left( \lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3 \right) + \sum_{k=1}^{N} \frac{1}{d_k} (J - 1)^{2k} \tag{3.10}
\]

where \( \tilde{\lambda}_P (P = 1, 2, 3) \) are deviatoric principal stretches and \( \lambda_P \) are the principal stretches of the left Cauchy-Green tensor.
3.4 Identification of Hyperelliptic Models

ANSYS provides a curve fitting method to define a hyperplastic material using the experimental test data. The curve fitting capability in ANSYS provides a simple and effective method for estimating material properties by comparing the experimental data with hyperelastic strain energy function models. The average data are fitted into several different hyperelastic models with ANSYS Workbench (Release 18.1, ANSYS, Inc.). The steps to perform curve fitting in ANSYS are as follows:

- Prepare and input experimental data (stress–strain test data) into ANSYS Engineering data module.
- Perform curve fitting analysis with different strain energy models.
- View the fitting results graphically and compare the fitted material constants with different models.
- Obtain the best fitting material coefficients and insert them into the database as a nonlinear hyperelastic material. The numerical values are used in future mechanical analyses.

In this section, the results obtained for each of the models (and sub-models) are presented.

3.4.1 Modelling results for ELASTOSIL M4061

The parameter values obtained for each strain energy function are presented in Table 3.6. Figures 3.4 to 3.7 display the curve fitting plots with different strain energy functions. Through the curve fitting plots, the Yeoh first-order model, Ogden third-order model and Mooney-Rivlin model conformed to the experimental stress–strain curve. The Mooney-Rivlin model performed as the best fitting model because of showing the smallest residual value and closely fitting curvature. However, the other models were not suitable for characterising the material properties for ELASTOSIL M4601. As presented in Table 3.6, the best constitutive model with parameter values proved to be the Mooney-Rivlin nine-parameter model, with parameter values $C_{01} = -2.3116 \times 10^5$ (Pa), $C_{02} = -3.0389 \times 10^6$ (Pa), $C_{03} = -3.805 \times 10^5$ (Pa), $C_{10} = 2.602 \times 10^5$ (Pa), $C_{11} =$
5.3913 \times 10^6 \text{ (Pa)}, C_{12} = 6.2285 \times 10^5 \text{ (Pa)}, C_{20} = -2.5167 \times 10^6 \text{ (Pa)}, C_{21} = 841.97 \text{ (Pa)} \text{ and } C_{30} = -48.85 \text{ (Pa)}.

Figure 3.4. Curve fitting results of (a) Arruda-Boyce model and (b) neo-Hookean model.

Figure 3.5. Energy function curve fitting plots for Mooney-Rivlin model: (a) two-parameter model, (b) three-parameter model, (c) five-parameter model, (d) nine-parameter model.
Figure 3.6. Yeoh model energy function curve fitting plot: (a) Yeoh first model, (b) Yeoh second model, (c) Yeoh third model.

Figure 3.7. Energy function curve fitting plot for Ogden model: (a) Ogden first model, (b) Ogden second model.
Table 3.6. Coefficients and material constants of Arruda-Boyce, neo-Hookean, Blatz-Ko, Mooney-Rivlin, polynomial, Yeoh and Ogden models calculated in ANSYS for Elastomer M4601.

<table>
<thead>
<tr>
<th>Hyperelastic Models</th>
<th>Parameter Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neo-Hookean</td>
<td>Initial shear modulus, $M_u = 1.5837 \times 10^5$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Residual: 235.91</td>
</tr>
<tr>
<td>Arruda-Boyce</td>
<td>Initial shear modulus, $M_u = 1.3249 \times 10^5$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Limiting network stretch: 4.9156</td>
</tr>
<tr>
<td></td>
<td>Residual: 89.743</td>
</tr>
<tr>
<td>Blatz-Ko</td>
<td>Initial shear modulus, $M_u = 2.4098 \times 10^5$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Residual: 711.18</td>
</tr>
<tr>
<td>Mooney-Rivlin two-parameter</td>
<td>Material constant, $C_{01} = -1.4891 \times 10^5$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{10} = 1.5055 \times 10^5$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Residual: 85.15</td>
</tr>
<tr>
<td>Mooney-Rivlin three-parameter</td>
<td>Material constant, $C_{01} = 6.849.8$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{10} = 35,539$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{11} = 8,033.9$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Residual: 6.8544</td>
</tr>
<tr>
<td>Mooney-Rivlin five-parameter</td>
<td>Material constant, $C_{01} = -1.3429 \times 10^5$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{10} = -82,019$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{11} = 1.4703 \times 10^5$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{12} = 29,439$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{20} = -2,418.2$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Residual: 2.3169</td>
</tr>
<tr>
<td>Mooney-Rivlin nine-parameter</td>
<td>Material constant, $C_{01} = -2.3116 \times 10^5$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{02} = -3.0389 \times 10^6$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{03} = -3.805 \times 10^5$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{10} = 2.602 \times 10^5$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{11} = 5.3913 \times 10^6$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{12} = 6.2285 \times 10^5$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{20} = -2.5167 \times 10^6$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{21} = 841.97$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{30} = -48.85$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Residual: 2.2507</td>
</tr>
</tbody>
</table>

59
Polynomial first order  
Material constant, $C_{01} = -1.4891 \times 10^5$ (Pa)
Material constant, $C_{02} = 1.5 \times 10^6$ (Pa)
Residual: 85.15

Yeoh first order  
Material constant, $C_{10} = 79,184$ (Pa)
Residual: 235.91

Yeoh second order  
Material constant, $C_{10} = 53,902$
Material constant, $C_{20} = 1,310.5$
Residual: 23.305

Yeoh third order  
Material constant, $C_{10} = 45,131$
Material constant, $C_{20} = 2,503$
Material constant, $C_{30} = -13.492$
Residual: 3.7989

Ogden  
Not matching

### 3.4.2 Modelling results for soft translucent silicone

The parameter values obtained for each strain energy function for the soft translucent silicone are presented in Table 3.7. The Mooney-Rivlin nine-parameter model proved the best constitutive model, with parameters values of $C_{01} = 11,683$ (Pa), $C_{02} = 1.7908 \times 10^6$ (Pa), $C_{03} = 2.264 \times 10^5$ (Pa), $C_{10} = -5,853.6$ (Pa), $C_{11} = -3.3685 \times 10^6$ (Pa), $C_{12} = -3.988 \times 10^5$ (Pa), $C_{20} = 1.6102 \times 10^6$ (Pa), $C_{21} = -493.29$ (Pa) and $C_{30} = 23.881$ (Pa). The relationship between the experimental data and Mooney-Rivlin model is shown in Figure 3.8.

![Figure 3.8. Energy function curve fitting plot for Mooney-Rivlin model.](image-url)
Table 3.7. Coefficients and material constants for Arruda-Boyce, neo-Hookean, Blatz-Ko, Mooney-Rivlin, polynomial, Yeoh and Ogden models calculated in ANSYS for Elastomer M4601.

<table>
<thead>
<tr>
<th>Hyperelastic Models</th>
<th>Parameter Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neo-Hookean</td>
<td>Initial shear modulus, $M_\text{u} = 20,867$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Residual: 342.11</td>
</tr>
<tr>
<td>Arruda-Boyce</td>
<td>Initial shear modulus, $M_\text{u} = 17,483$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Limiting network stretch: $-5.3058$</td>
</tr>
<tr>
<td></td>
<td>Residual: 90.948</td>
</tr>
<tr>
<td>Blatz-Ko</td>
<td>Not matching</td>
</tr>
<tr>
<td>Mooney-Rivlin two-parameter</td>
<td>Material constant, $C_{01} = -17,227$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{10} = 17,800$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Residual: 214.55</td>
</tr>
<tr>
<td>Mooney-Rivlin three-parameter</td>
<td>Material constant, $C_{01} = 12,488$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{10} = -3,540.5$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{10} = 1,443.4$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Residual: 20.146</td>
</tr>
<tr>
<td>Mooney-Rivlin five-parameter</td>
<td>Material constant, $C_{01} = -21,272$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{10} = -8,657.2$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{10} = 25,582$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{11} = 1,260.8$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{20} = 64.194$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Residual: 6.2738</td>
</tr>
<tr>
<td>Mooney-Rivlin nine-parameter</td>
<td>Material constant, $C_{01} = 11,683$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{02} = 1.7908 \times 10^6$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{03} = 2.264 \times 10^5$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{10} = -5,853.6$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{11} = -3.3685 \times 10^6$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{12} = -3.988 \times 10^5$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{20} = 1.6102 \times 10^6$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{21} = -493.29$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{30} = 23.881$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Residual: 2.1295</td>
</tr>
<tr>
<td>Yeoh first order</td>
<td>Material constant, $C_{10} = 10,433$ (Pa)</td>
</tr>
</tbody>
</table>
3.4.3 Modelling results for Ecoflex 00-10

The parameter values of Ecoflex 00-10 obtained for each strain energy function are presented in Table 3.8. The Mooney-Rivlin nine-parameter model proved the best constitutive model, with parameters value of $C_{01} = 11,683$ (Pa), $C_{02} = 1.7908 \times 10^6$ (Pa), $C_{03} = 2.264 \times 10^5$ (Pa), $C_{10} = -5,853.6$ (Pa), $C_{11} = -3.3685 \times 10^6$ (Pa), $C_{12} = -3.988 \times 10^5$ (Pa), $C_{20} = 1.6102 \times 10^6$ (Pa), $C_{21} = -493.29$ (Pa) and $C_{30} = 23.881$ (Pa). The relationship between the experimental data and Mooney-Rivlin model is shown in Figure 3.9.

![Figure 3.9. Energy function curve fitting plot for Mooney-Rivlin model for Ecoflex 00-10.](image)
Table 3.8. Coefficients and material constants of Arruda-Boyce, neo-Hookean, Blatz-Ko, Mooney-Rivlin, polynomial, Yeoh and Ogden models calculated in ANSYS for Ecoflex 00-10.

<table>
<thead>
<tr>
<th>Hyperelastic Models</th>
<th>Parameter Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neo-Hookean</td>
<td>Initial shear modulus, $M_H = 35,903$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Residual: 484.77</td>
</tr>
<tr>
<td>Arruda-Boyce</td>
<td>Initial shear modulus, $M_H = 29,454$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Limiting network stretch: 4.6547</td>
</tr>
<tr>
<td></td>
<td>Residual: 297.47</td>
</tr>
<tr>
<td>Blatz-Ko</td>
<td>Not matching</td>
</tr>
<tr>
<td>Mooney-Rivlin two-parameter</td>
<td>Material constant, $C_{01} = -45,246$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{10} = 46,962$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Residual: 47.338</td>
</tr>
<tr>
<td>Mooney-Rivlin three-parameter</td>
<td>Material constant, $C_{01} = -32,769$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{10} = 35,447$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{10} = 837.6$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Residual: 34.151</td>
</tr>
<tr>
<td>Mooney-Rivlin five-parameter</td>
<td>Material constant, $C_{01} = -1.4963 \times 10^5$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{10} = -59,466$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{10} = 1.5026 \times 10^5$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{11} = 11,427$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{20} = -1,015.5$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Residual: 10.779</td>
</tr>
<tr>
<td>Mooney-Rivlin nine-parameter</td>
<td>Material constant, $C_{01} = -5.1366 \times 10^5$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{02} = -1.1024 \times 10^7$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{03} = -1.4587 \times 10^6$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{10} = 5.1142 \times 10^5$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{11} = 1.9464 \times 10^7$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{12} = 2.32 \times 10^6$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{20} = -8.9766 \times 10^6$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{21} = 1,707.2$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Material constant, $C_{30} = -92.695$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Residual: 3.7216</td>
</tr>
<tr>
<td>Yeoh first order</td>
<td>Material constant, $C_{10} = 17,951$ (Pa)</td>
</tr>
</tbody>
</table>
3.4.4 Model fitting results for FilaFlex

The Mooney-Rivlin nine-parameter model showed a good match with the experimental data as shown in Figure 3.10, with the following parameter values: material constant $C_{01} = -3.6546 \times 10^7$ (Pa), $C_{02} = -4.4964 \times 10^8$ (Pa), $C_{03} = -6.0076 \times 10^7$ (Pa), $C_{10} = 3.7227 \times 10^7$ (Pa), $C_{11} = 7.6055 \times 10^8$ (Pa), $C_{12} = 8.5319 \times 10^7$ (Pa), $C_{20} = -3.431 \times 10^8$ (Pa), $C_{21} = 69,852$ (Pa) and $C_{30} = -4,145.2$ (Pa).

Figure 3.10. Energy function curve fitting plot for Mooney-Rivlin model for FilaFlex.

Table 3.9. Coefficients and material constants of Arruda-Boyce, neo-Hookean, Blatz-Ko, Mooney-Rivlin, polynomial, Yeoh and Ogden models calculated in ANSYS for FilaFlex.

<table>
<thead>
<tr>
<th>Hyperelastic Models</th>
<th>Parameter Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neo-Hookean</td>
<td>Initial shear modulus, $M_u = 2.1174 \times 10^6$ (Pa)</td>
</tr>
<tr>
<td></td>
<td>Residual: 5.3583</td>
</tr>
<tr>
<td>Arruda-Boyce</td>
<td>Initial shear modulus, $M_u = 2.1174 \times 10^6$ (Pa)</td>
</tr>
</tbody>
</table>
Limiting network stretch: \(-7.9636 \times 10^8\) (Pa)

Residual: 5.3583

**Blatz-Ko**

Initial shear modulus, \(\mu = 2.4098 \times 10^5\) (Pa)

Residual: 711.18

**Mooney-Rivlin two-parameter**

Material constant, \(C_{01} = 1.9464 \times 10^6\) (Pa)

Material constant, \(C_{10} = 6.5804 \times 10^5\) (Pa)

Residual: 2.0197

**Mooney-Rivlin three-parameter**

Material constant, \(C_{01} = 4.475 \times 10^5\) (Pa)

Material constant, \(C_{02} = 1.5882 \times 10^6\) (Pa)

Material constant, \(C_{11} = -43.874\) (Pa)

Residual: 1.0415

**Mooney-Rivlin five-parameter**

Material constant, \(C_{01} = -9.3035 \times 10^6\) (Pa)

Material constant, \(C_{10} = -3.465 \times 10^6\) (Pa)

Material constant, \(C_{10} = 1.0585 \times 10^7\) (Pa)

Material constant, \(C_{11} = 2.9806 \times 10^5\) (Pa)

Material constant, \(C_{20} = -29.065\) (Pa)

Residual: 0.25371

**Mooney-Rivlin nine-parameter**

Material constant, \(C_{01} = -3.6546 \times 10^7\) (Pa)

Material constant, \(C_{02} = -4.4964 \times 10^8\) (Pa)

Material constant, \(C_{03} = -6.0076 \times 10^7\) (Pa)

Material constant, \(C_{10} = 3.7227 \times 10^7\) (Pa)

Material constant, \(C_{11} = 7.6055 \times 10^8\) (Pa)

Material constant, \(C_{12} = 8.5319 \times 10^7\) (Pa)

Material constant, \(C_{20} = -3.431 \times 10^8\) (Pa)

Material constant, \(C_{21} = 69,852\) (Pa)

Material constant, \(C_{30} = -4.145.2\) (Pa)

Residual: 0.039095

**Yeoh first order**

Material constant, \(C_{10} = 1.0587 \times 10^6\) (Pa)

Residual: 5.3583

**Yeoh second order**

Material constant, \(C_{10} = 1.5668 \times 10^6\) (Pa)

Material constant, \(C_{20} = -7,197.6\) (Pa)

Residual: 1.5957

**Yeoh third order**

Material constant, \(C_{10} = 1.8054 \times 10^6\) (Pa)
Material constant, $C_{20} = -18.033$ (Pa)
Material constant, $C_{30} = 107.94$ (Pa)
Residual: 1.0739

3.5 Conclusion

This chapter characterised the material properties of ELASTOSIL M4061, Ecoflex 00-10, soft translucent silicones and FilaFlex through a uniaxial tensile test undertaken following ISO 37 standard. A 3D additive manufacturing method was used to fabricate the test samples. The average experimental data for different materials were used to fit with the strain energy functions. Hyperelastic materials are nonlinear materials that can generate large deformation. As a result of the highly nonlinear behaviour, the characterisation of hyperelasticity was determined through a stress–strain test and FEM. This chapter has presented a thorough comparison of seven models for hyperelastic materials available in ANSYS, including the Mooney-Rivlin, neo-Hookean, polynomial, Blatz-Ko, Arruda-Boyce, Yeoh and Ogden models. Strain energy functions were used to determine the material properties. The abilities of these models were analysed through experimentally obtained uniaxial tensile data. The best fitting material coefficients were selected and imported into the database as a nonlinear hyperelastic material. The numerical values are used in the finite element analyses conducted in this thesis.

This study showed that the Mooney-Rivlin model can be used to characterise hyperelasticity in FEM because of its excellent match with experimental stress–strain data under a large deformation. The material constants calculated in this chapter are used in the simulations to optimise the structural design presented in Chapters 4 and 5.
Chapter 4

Methodology for Structural Optimisation of a Soft Pneumatic Actuator

4.1. Introduction

The soft PneuNet actuators that can generate significant deflection have considerable potential for soft robotic applications, especially for medical devices. They are cheap, lightweight and safe during human-robot interaction and can deliver high power densities with a remarkable mechanical output [93, 94]. Pneumatic actuators offer better soft actuation features than those of the conventional actuators due to their convenience and simplicity. With the recent progress in soft and processable smart materials, soft actuation concepts that make use of pneumatic networks in a slender body have been proposed [93, 94, 103, 113, 226]. Such pneumatic actuators can generate bending and linear movements, offering a high potential to be employed in soft robotics and medical applications due to their inherent compliance and safety. However, the bending performance of this type of actuator strongly depends on the design parameters of the channels. Therefore, there is a need for an efficient method to optimise the bending angle of the PneuNet actuators.

This chapter investigates the effects of various design parameters on the actuation performance of a PneuNet actuator, optimises its structure using finite element method (FEM) and subsequently quantifies the performance of the resulting actuator topology experimentally. The effects of the structural parameters—including the operation pressure, wall thickness, gap between the chambers, bottom layer thickness and geometry of the channel cross-section—on the deformation and bending angle of the actuator are evaluated to optimise the performance of the pneumatic actuator. A global ANOVA is performed to investigate how the variables affect the mechanical output of the actuator and which variables significantly affect the deformation or bending angle. After the parameter optimisation, the pneumatic channel with a 4.5 mm bottom layer thickness, 1.5 mm wall thickness and 1.5 mm gap size are recommended to perform an optimised bending motion for the PneuNet actuator. The FEM optimised results are verified experimentally, which indicates a satisfactory match between the simulation
and experimental results. This design optimisation method based on FEM and ANOVA analysis can be extended to the topology optimisation of other actuators.

### 4.2. Parametric Investigation for Structure Optimisation of the Actuator

The objectives of this section are as follows. First, this section develops a finite element model that can predict the mechanical output or bending performance of the pneumatic actuator. Second, it investigates the effects of primary parameters. Third, it optimises the structure of the actuator, which is fixed at one end and free at the other end, like a cantilever beam. This study conducted the finite element modelling in ANSYS Workbench using static structural analysis. The left surface of the soft actuator was fixed, acting as the fixed boundary, and the pressure inputs were applied equally on the inner surfaces of each chamber. Large deformation effects were taken into account in the finite element model. To optimise the performance of the pneumatic actuator, this study examined the effects of structural parameters—including the operation pressure, bottom layer thickness, wall thickness, gap between adjacent channels and cross-section—on the deformation and bending angle of the actuator.

#### 4.2.1. Structure of the actuator

The pneumatic actuator described in this study consisted of a series of channels arranged in a row, also known as PneuNet actuator [93, 94, 103]. The PneuNet structures in this study is based on the design described in [93], which can provide high rates of actuations with high reliability. The actuation source was compressed air, which could provide the force for the system. When the actuator was inflated, the channels expanded, causing the actuator to deform in the longitudinal direction. The actuator consisted of two layers—the upper active layer and passive bottom layer, as shown in Figure 4.1 (a). When compressed air was input to the channels, the active layer deformed, as shown in Figure 4.1 (c). Upon increasing the input pressure, a significant increase in the deformation and bending angle was observed. There was an approximately linear relationship between the pressure and bending angle, as revealed in Figure 4.1 (b), under this pressure range.
Meshing is the first step of the computational simulation process. The precision and convergence of the simulation results can be affected by the mesh method. The mesh quality will also affect the simulation speed. Generally, the more elements generated by a better mesh, the slower and better the solution will be. The mesh used in this study is shown in Figure 4.1 (d). The minimum edge length for the mesh was 1.0 mm.

Figure 4.1. (a) Longitudinal cross-section of actuator. (b) Effect of pressure on bending angle. (c) Bending angle under different input pressures. (d) Meshing.
4.2.2. Material selection

Silicone rubber was selected as the actuator material for a number of reasons. This material is inexpensive and can be moulded into a variety of shapes with a low actuation pressure or stress, and exhibits properties desirable for the actuator. Figure 4.2 indicates that, with an increase in Young’s modulus, the bending deformation decreased. As shown in Figure 4.2, when Young’s modulus was 0.1 MPa, the deformation was twice that at 0.2 MPa, and this turned into an exponentially decreasing trend. There was an inverse relationship between the Young’s modulus of the materials and the deformation of the actuator under high pressures.

![Figure 4.2. Bending angle change with Young’s modulus of actuator material.](image)

The material should have reasonable stiffness to provide sufficient bending angle and blocking force to perform grasping tasks for soft robotic gripper applications. In addition, the bursting of pneumatic channels should also be considered when selecting materials. Figure 4.3 illustrates that actuators made from various silicon rubbers with different moduli of elasticity generate different bending angles under the same test pressure (20 kPa).
Figure 4.3. Effect of material stiffness on bending angles under same test pressure (20 kPa).

The biocompatibility of two selected silicone rubbers (M4601 and Ecoflex 00-10) was tested using cancer cells. The silicone rubber had two liquid parts, and, after mixing these two parts together at a fixed mass ratio, the rubber cured under room temperature. Moreover, the cured rubber was exposed to a UV lamp to disinfect and kill the microorganisms. Then the same amount of cell culture fluid was poured into the silicone rubber, and a pure fluid was used as the reference substance. The three groups of cells were placed in the incubator and observed under a microscope, and the cell viability was tested every day.
Figure 4.4. Biocompatible test results of M4601: (a) experimental process and (b) observation of cell viability.
The cells in M4601 and cell culture fluid were kept alive for three days, and the cell proliferation was at normal speed as shown in Figure 4.4. The number of cells increased during the three days, so this material was biocompatible. Moreover, cells in the transparent material (Ecoflex 00-10) were kept alive for the first 24 to 48 hours. In the first 24 hours, the cells could still divide and the amount increased, and then the viability of the cells decreased. Therefore, M4601 was biocompatible and was subsequently used in our design. The biocompatibility of the material was important, as progress in soft robotics will have a significant effect on medical devices, especially for assistive, rehabilitation and prosthetic devices, where human–machine interaction is essential.

There are several methods to test the mechanical measurement of soft material characterisation. In [23], the measurement of three elastomers—Sylgard 184, SmoothSil 950 and Ecoflex 00-30—was demonstrated. In this thesis, the silicone rubber M4601 was used as the test material. The material characterisation was analysed using curve fitting method through ANSYS and the experimental tensile test in Chapter 3. The Mooney-Rivlin nine-parameter model proved to be the best constitutive model, with the following parameter values: \( C_{01} = -2.3116 \times 10^5 \) (Pa), \( C_{02} = -3.0389 \times 10^6 \) (Pa), \( C_{03} = -3.805 \times 10^5 \) (Pa), \( C_{10} = 2.602 \times 10^5 \) (Pa), \( C_{11} = 5.3913 \times 10^6 \) (Pa), \( C_{12} = 6.2285 \times 10^5 \) (Pa), \( C_{20} = -2.5167 \times 10^6 \) (Pa), \( C_{21} = 841.97 \) (Pa) and \( C_{30} = -48.85 \) (Pa).

As a result of the composite structure of the actuators with PneuNets inside, the effective modulus of elasticity of the actuator is different from the specific modulus of elasticity of the material. The effective modulus of elasticity was adopted in the simulations of the actuator. M4601 has an effective modulus of elasticity of 386.66 kPa, which was proposed and identified in this study [227] using numerical and experimental results. Some physical properties of the material were presented in Chapter 3. The modulus of elasticity for hyperelastic materials is not constant, and the movement of the actuator is nonlinear. Both the calculated effective modulus and material contents tested can be used in ANSYS for structural optimisation.
4.2.3 Analysis of variance

Several parameters of the pneumatic actuator were studied in the finite element model. To reduce the simulation and experimental efforts to a manageable size, only the bottom layer thickness, gap between the adjacent channels, wall thickness of the channels and shape of the cross-section were considered for the design optimisation of the proposed actuator concept. To investigate how the variables affected the deformation of the actuator and which variables significantly affected the deformation, this study performed a global ANOVA conducted at a 95% confidence level using Minitab 17.

Table 4.1. Variables employed in the simulation process.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall thickness (mm)</td>
<td>1 1.25 1.5 1.75</td>
</tr>
<tr>
<td>Bottom layer thickness (mm)</td>
<td>4.5 5 5.5 6</td>
</tr>
<tr>
<td>Gap between adjacent channels (mm)</td>
<td>1 1.25 1.5 1.75</td>
</tr>
</tbody>
</table>

To examine how the actuator geometry affected the actuator bending angle (and strain), the overall length of 140 mm and width of 20 mm of the actuator were kept constant. Further, the overall volume of 512 m³ and surface area of each channel were held constant. In this analysis, the bottom layer thickness (4.5 to 6 mm), wall thickness (1 to 1.75 mm) and gap sizes (1 to 1.75 mm)—each with four levels—were tested with an input pressure of 20 kPa under the same simulation environment. The effects of all variables were analysed using the full factorial design module. The parameters listed in Table 4.1 were used in the simulation. Sixty-four different parameters considered in the simulation results were used in the analysis. The residual plot for the bending angle shown in Figure 4.5 (a) illustrates the distribution of data from the simulation results. A random pattern is also presented in the graph of residual versus case numbers, as shown in Figure 4.5 (b), thereby indicating that the ANOVA results were reasonable.
Table 4.2. ANOVA results for bending angle versus wall thickness, gap size and bottom thickness.

<table>
<thead>
<tr>
<th>Source</th>
<th>DOF</th>
<th>F-value</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom layer thickness</td>
<td>3</td>
<td>332.91</td>
<td>&lt; 5%</td>
</tr>
<tr>
<td>Gap size</td>
<td>3</td>
<td>13.36</td>
<td>&lt; 5%</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>3</td>
<td>185.55</td>
<td>&lt; 5%</td>
</tr>
</tbody>
</table>

The ANOVA results are summarised in Table 4.2. The F-value represents the mean square error to residual, which determines the importance of one factor. The variable with the highest F-value has the most significant effect on the response variable. The P-value represents the significance degree. The analysis is performed at a 5% significance level, so that, when P is less than 5%, the parameter has a significant effect on the variable result. For example, since the P-value of all three parameters was less than 5% and the corresponding F-value of 332.91 for the bottom layer thickness was the highest among the three parameters, the bottom layer thickness was considered the most significant factor influencing the bending angle, followed by the wall thickness and finally the gap size. A detailed analysis of the effects of these three parameters on bending performance is provided in the following subsections.

4.2.4. Effect of bottom layer thickness

The parametric optimisation for the thickness of the unpressurised bottom layer was based on the PneuNet actuator model. M4601 silicone rubber was used in the experimental work. The other parameters were kept constant, except for the lower layer.
thickness. The gap size and wall thickness were 1.5 mm, which was constant in this simulation setting. To further investigate the effect of the most significant parameter obtained through the ANOVA results, an extensive range of bottom layer thickness was adopted. Figure 4.6 displays that the bending angle followed a parabolic relationship with the bottom layer thickness. For a smaller bottom layer thickness, the bending angle increased when the bottom layer increased from 3 to 4.5 mm. The bending angle reached the maximum value of approximately 172° for a bottom layer thickness of 4.5 mm. However, the bending angle decreased with further increase in the bottom layer thickness from 4.5 to 8.5 mm. The researchers postulate that this was primarily a result of the fact that the area moment of inertia increased with these values of bottom layer thickness, creating more resistance to bending, rather than increasing the bending angle. Consequently, if the bottom layer is the only design variable that should be considered, a bottom layer of 4.5 mm is the optimised value to provide the largest bending angle.

![Figure 4.6. Bending angle versus bottom layer thickness.](image)

4.2.5. Effect of gap between adjacent channels

Figure 4.7 displays the variation of the bending angle with the gap between the adjacent channels, where the bending angle of the actuator showed a decreasing trend with gap size. A smaller gap can be expected to generate a larger bending angle, so that a smaller gap could be used. When 0.5 mm and 1 mm gaps were used, the adjacent channels would touch each other. However, there would not be contact between the adjacent channels when 2 mm gaps were applied. Although the interaction force between the channels can potentially generate larger bending angles, it may also lead to damaging
the channels. Therefore, a 1.5 mm gap is more appropriate in this design to avoid bursting problems and to achieve a relatively large bending angle.

Figure 4.7. (a) Effect of gap between adjacent channels. (b) Variation of bending angle with gap size between adjacent channels.
4.2.6. Effect of channel wall thickness

The second design parameter considered was the wall thickness (the distance between the pneumatic channel and outside surface) of each channel, changing from 1.0 to 1.75 mm. Figure 4.8 presents the effect of the wall thickness on bending angles—-with a decrease in wall thickness, the bending angle grew larger in a linear fashion.

![Figure 4.8. Variation of bending angle with wall thickness.](image)

The whole actuator was in the form of a cantilever beam when it was actuating and generating bending motion. Figure 4.9 displays the cross-section of the actuator chamber, where \(a\), \(b\), \(a_0\), \(b_0\), \(t\) and \(w\) represent the inside dimensions, outside dimensions, bottom layer thickness and wall thickness, respectively. \(a\), \(b\) and \(t\) were kept constant in this analysis to investigate the effect of wall thickness. The deformation...
of the chamber was caused by the offset, \( e \), between the centre of pressure, \( P \), and the neutral axis, \( \text{N.A.} \) [227], as shown in Figure 4.9, and the cantilever will bend towards the neutral axis. The radius of curvature is given by:

\[
\frac{1}{R} = \frac{PAe}{EI}
\]  

(4.1)

where \( R \), \( P \), \( A \), \( E \) and \( I \) are the radius of the curvature, pressure, area inside the channel, modulus of elasticity and area moment of inertia of the deflected beam or actuator, respectively. The change in wall thickness can also result in a change in the area moment of inertia, which will affect the curvature. In this research, \( R \), \( P \), \( A \) and \( E \) were all kept constant. Therefore, the radius of curvature was mainly affected by the ratio of \( e/I \). The dimensions of the cross-section are displayed in Figure 4.9, and the centre of pressure and neutral axis, \( \text{N.A.} \), are given by:

\[
P = \frac{\sum_{i=1}^{n} A_i y_i}{\sum_{i=1}^{n} A_i} = \frac{b}{2}
\]  

(4.2)

\[
\text{N.A.} = \frac{\sum_{i=1}^{n} A_i y_i}{\sum_{i=1}^{n} A_i} = \frac{1}{2}a_0b_0^2 - ab(t + \frac{1}{2}b)
\]  

(4.3)

\[
a_0 = a + 2w
\]  

(4.4)

\[
b_0 = b + t + w
\]  

(4.5)

The area moment of inertia, \( I \), about the centroid axis of a cross-section is given by:

\[
I = \int y^2 dA
\]  

(4.6)

where \( y \) is the perpendicular distance from axis \( x \) to the element \( dA \). There is a distance between the centroid axis of the outside rectangle and inside rectangle; thus, this study employed a parallel-axis theorem to obtain the moment of inertia of the cross-section about its centroid axis. The theorem is given by:

\[
I_x = I_{x1} + Ad^2
\]  

(4.7)

where \( I_{x1} \) is the moment of inertia about its own centroid axis and \( I_x \) is the moment of inertia about any parallel axis with a distance of \( d \). In the simulations, the wall thickness
varied from 1 to 1.75 mm with the thickness increments of 0.25 mm. Then the distance between the centre of pressure and the neutral axis, $e$, and area moment of inertia, $I$, were calculated. The results are shown in Figure 4.10—as the wall thickness increased, the $e/I$ ratio became smaller, which meant the bending angle became smaller. These results agree with the simulation results in Figure 4.8.

![Figure 4.10. Variation of $e/I$ ratio with wall thickness.](image)

The wall thickness is an important variable because a thin wall will easily burst, and a thick wall requires a relatively high pressure to generate the same bending angle. However, when a thin wall is applied, it is relatively easy for the chambers to be damaged. Thus, these two factors should be considered together when selecting the wall thickness. The wall should be thin enough to generate full bending, and thick enough to bear the actuation pressure. To select an appropriate wall thickness, the wall thickness and bottom layer thickness are considered together, as shown in Figure 4.11. The results
in Figure 4.11 indicate that, before the maximum point, the outcomes were mainly affected by the bottom layer thickness. The bottom layer thickness affected the bending angle more than the wall thickness, which agreed well with the ANOVA results. However, a 1 mm wall thickness and 4.5 mm bottom layer thickness can be expected to generate the largest bending angle. Given that a low-cost 3D printing method was used to fabricate the actuator, the fabrication accuracy and bursting issues needed to be considered; thus, a 1.5 mm wall thickness was preferred in this design. Based on the analysis of the simulation results and several experimental testing results, a 4.5 mm bottom layer thickness, 1.5 mm wall thickness and 1.5 mm gap size is recommended to be used in the pneumatic actuator design.

4.2.7. Effect of cross-section

Figure 4.12 displays the variation of the bending angle with the channel cross-sections, which consisted of: (i) a rectangular cross-section, (ii) a honeycomb cross-section, (iii) a half round cross-section and (iv) a round cross-section, as illustrated in Figure 4.12 (b). Figure 4.12 displays that the bending angle can be affected by the cross-section, while the actuator with a round cross-section can provide the smallest bending, and the actuator with a rectangular, honeycomb and half round can provide similar bending angles under the same input pressure. In this study, the volume of the channels was kept constant. The thickness of the bottom layer of 4.5 mm, wall thickness of 1.5 mm and total length of 104 mm were also held constant. However, the volume of the entire structure was different. The bending angle, $\theta$, was directly proportional to the ratio of the total channel volume ($V_c$) to the total (overall) structural volume ($V_s$). It must be noted that, for a pneumatic actuation system based on flexible chambers, the input work equals the gauge pressure multiplied by the change in chamber volume. The pressure was constant for all the cross-sections, which left the volume change as the primary variable to compare and quantify the bending performance of various cross-sections. The numerical results indicated that the ratio of $V_c/V_s$ for the round cross-section was the smallest, which meant that the actuator with the round cross-section generated the lowest bending performance (angle).

When the pressure was below 25 kPa, the bending angle showed a nearly linear relationship with the pressure. When the pressure was over 25 kPa, the adjacent
channels touched and pushed each other. As a result of their interaction forces, the relationship between bending angle and pressure was no longer linear because of a more complicated interaction occurring under higher pressures.

Figure 4.12. Variation of bending angle with different cross-sections: (a) simulation results; (b) cross-sections considered in this study: (1) rectangular cross-section, (2) honeycomb cross-section, (3) half round cross-section and (4) round cross-section; (c) bending shape with different cross-sections under 35 kPa pressure.

4.3. Experiment Setup

4.3.1. Fabrication of soft pneumatic actuator

The fabrication process for the pneumatic actuator is shown in Figure 4.13, and the fabricated actuator is shown in Figure 4.13 (d). The pneumatic actuator consisted of two
layers that were moulded separately and then combined after curing. The upper layer was the active layer composed of several channels, and the lower layer was the passive layer. The liquid silicone rubber was poured separately into the moulds, which were prepared using a low-cost 3D printer. These two parts were then cured at a certain temperature, and a thin layer of the uncured silicone rubber was used as the glue to bond these two pieces together. The fabrication steps were as follows:

(i) The 3D printed mould was prepared using a low-cost 3D printer. The mould consisted of three parts.

(ii) Two silicone rubbers were prepared, with the silicone and curing agent mixed with a 9:1 volume/weight ratio. The mixed liquid was then poured into the 3D-printed moulds for moulding and curing. The stirring and pouring processes generated numerous air bubbles, which would cause a leaking problem for the structure. Therefore, after the two parts were mixed well and the mixed liquid was placed into the mould, a vacuum pump was used to remove the air bubbles, as shown in Figure 4.13 (a).

(iii) Curing: The mould and liquid were placed in the oven until these two parts of the main body were cured at the particular temperature (the M4601 was cured at 70°C for 20 minutes; the curing time depends on the temperature).

(iv) The two parts of the actuator were removed from the mould. The two parts were combined using uncured silicone rubber as the glue.
Figure 4.13. Fabrication procedure and moulded actuators: (a) preparation of silicone rubber, (b) fabrication procedure, (c) 3D printed mould, (d) moulded actuator.
4.3.2. Control unit

A control unit is used to control and operate fluidic actuators. The aim of this control unit is to test the performance of the fluidic actuators quickly. The unit consists of a pump, valves, a power regulator, a microcontroller, pressure sensors and switches as shown in Figure 4.14 and 4.15. The pump is used to provide pressurised air to the system. The solenoid valves can directly control the flow of air in the system. The pulse-width modulation is used to regulate the pressure and control the operation of the valves. The pressure sensors provide feedback on the system pressure. The control unit can be controlled by manually opening and closing the switches and knobs or can be operated by the microcontroller [137].

![Figure 4.14. Layout of control unit.](image1)

![Figure 4.15. Assembled control unit.](image2)
4.4. Comparison of Simulation and Experimental Results

Experiments were conducted to verify the simulation results. The optimised parameters selected in Section 4.2 were used in the experimental samples. The pneumatic actuator was actuated with a miniature pump. The actuators with rectangular, honeycomb, half round and round cross-sections were fabricated using the process outlined in Figure 4.13, and then the bending angles under the same pressure were compared. For each cross-section, three measurements were performed, and the average value was selected as the final result. The simulation and experimental results agreed well, as shown in Figure 4.16.

![Image](image1.jpg)  
(a)  
![Image](image2.jpg)  
(b)  
![Image](image3.jpg)  
(c)  
![Image](image4.jpg)  
(d)

Figure 4.16. Comparison of experimental and simulation results for bending angle: (a) bending shape of rectangular cross-section actuator; (b) experimental results with four different cross-sections; (c) comparison of experimental and simulation results with rectangular cross-section; (d) comparison of experimental and simulation results with half round cross-section.
The actuator with the round cross-section provided the smallest bending angle. There appeared to be non-negligible deviation between the simulation and experimental results, as shown in Figure 4.16 (c) and (d), where the predicted bending angle was larger than the experimental results. Given that the simulation was conducted in a relatively ideal environment, some pressure losses (such as in the PneuNet and associated pipes) were not considered in the simulation conditions and results. This issue and some other experimental errors were unavoidable and may have resulted in the offset between the experimental and simulation results.

The blocking force was tested, and the results are shown in Figure 4.17. A six-axis multi-axis force sensor (K6D Multicomponent Sensor, ME-Meßsysteme GmbH, Neuendorfstr) was used to measure the force generated by the tip of the finger, which is the blocking force. One end of the actuator was fixed to act as a cantilever beam. As the input pressure increased, there was an increase in the output force. Before 30 kPa, the gradient increased slightly. When a relatively small pressure was applied to the actuator, the bending angle was small, and the blocking force was mainly caused by the weight of the actuator. The gradient increased significantly after 30 kPa. The sensor generated a resistance to the bending movements of the actuator when the input pressure was large enough. The actuator made contact with the sensor base and bent in an arch, as shown in Figure 4.17 (a). When inflated, the upper layer of the actuator extended and moved forward. The bending movements and contact with the sensor could be attributed to the increase in the blocking force. As shown in Figure 4.17 (b), the actuator with rectangular cross section can provide largest blocking force and the actuator with the round cross-section provided the smallest bending angle. This result can be extended to the design of other actuators with different chamber structures.
Figure 4.17. Blocking force test: (a) experimental setup to measure blocking force and bending shape during blocking force test process; (b) blocking force results.

4.5. Conclusions

This chapter aimed to optimise the structure of the PneuNet actuator. Different designs of the pneumatic channels were used to quantify the effects of the critical design parameters. This chapter presented a design optimisation methodology based on the FEM to optimise the actuator structure. The overall soft actuator design was optimised to meet the required bending performance. A methodology based on statistical analysis was employed to optimise the performance of a pneumatic actuator proposed for soft robotic applications. The effects of various actuator parameters were studied to obtain a better understanding of the actuation performance for a slender pneumatic actuator. By using the developed static structural model for the PneuNet actuator, the critical design parameters were numerically evaluated, including the effects of pressure, wall thickness, bottom layer thickness, gap size and cross-section shape of the channels on the actuator deformation. ANOVA analysis was performed to systematically determine
which actuator parameters significantly affected the deformation or bending angle of the actuator. After the simulations, the optimised actuator was fabricated, and experiments were undertaken to quantify the performance of the optimised actuator. The simulation and experimental results were compared and analysed. The optimisation method can be extended to the design of pneumatic actuators to fulfil more complicated tasks.
Chapter 5

Bio-inspired 3D-printed Helical Soft Pneumatic Actuators and Their Characterisation

5.1. Introduction

Nature abounds with complex 3D shapes and helices, which are some of the most common structures in nature and engineering. Examples include DNA strands [228], collagen triple helices [229], twining plant tendrils [230-232], the arms of an octopus [233], mechanical springs [234], Chaetoceros debilis and more [235-238]. Inspired by nature, various applications that mimic helical motions have been demonstrated in biomedical and soft robotic areas. SPAs are widely used in robotic applications, including grippers, manipulators, bio-inspired soft-bodied robotics, hand-assistive and rehabilitation devices, and micro and nano devices. To expand such applications, the SPAs should be purpose-built to generate application-specific complex motions with multiple degrees of freedom (DOF).

Based on their DOF, the current SPAs reported in the literature can be divided into three major groups:

1. one-dimensional: rectilinear contraction and extension motions [239]
2. two-dimensional: cyclic and bending motions
3. three-dimensional: helical, twisting, spiral and some other complicated motions.

The McKibben artificial muscle, which consists of a bladder covered in a shell of fibres, is the most frequently used and researched actuator with one-dimensional movement (contraction and extension) in robotic applications [97, 239, 240]. Examples of one-dimensional actuators include PAMs for robot arm applications [241-243], lower limb wearable robotic devices [244], prosthetic hands [245], manipulators [246] and so forth. However, actuators such as PAMs that generate one-dimensional movement are usually not suitable for soft robotic applications and, in particular, are not sufficiently flexible for bio-inspired soft robotic applications.
Bending shapes are simple and omnipresent in both nature and engineering. Some SPAs, such as PneuNets \([111, 114, 219, 247, 248]\) and PBAs \([102, 249]\), which can generate cyclic and bending motions, are among the most researched pneumatic actuators in the soft robotic field. A cyclic motion in a circular trajectory can easily be accomplished in soft systems using PneuNets \([93, 103, 161, 247, 248]\). Figure 5.1(b) shows the structure and working mechanism of PneuNets. To expand the applications and accomplish more complex tasks, SPAs that can generate more DOF are required. Creatures with helical shapes can provide efficient motions \([137]\), such as twisting plant tendrils for grasping and climbing as shown in Figure 5.1(a), elephant trunks for grasping, and octopus arms for swimming and hunting. Various helical actuators in soft robotic applications have been demonstrated in the literature. A helical SPA reported in \([133]\) can produce a helical motion by changing the stiffness of the hybrid material of which it is made. Some other applications include an underwater gripper \([250]\), 3D photonic actuators \([235]\), hydrogel-based helical actuators \([251]\) and SMA-based actuators \([238, 252]\). Helical applications using pneumatic actuators are limited primarily because of the lack of an efficient fabrication method \([253]\).

This chapter proposes a new 3D helical actuator using a low-cost 3D printer with a one-step manufacturing process to expand the applications in fully compliant soft robotics. The proposed actuator is based on multiple angled PneuNets to generate helical configurations and 3D movements upon their activation as described in \([254]\).
This chapter describes a bio-inspired, 3D-printed, low-cost, all-in-one-piece soft pneumatic helical actuator to expand the applications in fully compliant soft robotics. The helically configured rotating actuator is based on an optimised longitudinal array of pneumatically actuated angled chambers reported in the researchers' previous study [253], which can generate a 3D helical trajectory. The trajectory of the actuator is characterised by changing the length of the actuator and chamber angles. The FDM technique was used to manufacture the actuator. The printing settings were optimised to print an airtight helical actuator with a wall thickness of 0.64 mm. The trajectory of the actuator was recorded, and the blocking force was experimentally measured. The proposed helical actuator has a larger tip trajectory or larger work volume, and higher

Figure 5.1. (a) Soft grippers inspired by climbing tendrils [255]. (b) Basic structure of fast PneuNet actuators [93].
blocking force, indicating a higher mechanical output compared with a bending actuator of the same size and under the same input pressure.

5.2. 3D Additive Manufacturing

This study used an FDM printer (Creator Pro, FlashForge) to directly manufacture the SPAs. To create an airtight structure, the printing settings and extruding unit were modified and optimised carefully. Several testing samples—shown in Figure 5.2 (b)—were fabricated to optimise the printing parameters. An open-source slicing software (Slic3r) was used to optimise the printing settings. After several tests, the optimised printing settings were used to fabricate the airtight helical soft actuator, which has a wall thickness of 0.64 mm. The specific printing parameters for this method are summarised in Table 3.5.

5.3. Materials

As a result of its high elasticity and excellent abrasion resistance, FilaFlex (Recreus Industries SL), as a TPE, was selected as the filament to be used with the above FDM 3D printer to create the SPAs. Compared with several commercially available TPE filaments, FilaFlex has a relatively lower elastic modulus, which made it suitable for the fabrication of the 3D-printed, all-in-one actuator.

Uniaxial tensile tests were conducted to characterise the material properties in Chapter 3. The stress–strain relationship is nonlinear, and the curve fitting was used to determine the parameters. The average data were fitted into several different hyperelastic models (Mooney-Rivlin, Ogden, Yeoh and polynomial models) with ANSYS Workbench (release 18.1, ANSYS Inc.). The Mooney-Rivlin model with the following parameter values fitted the tensile test results well: \( C_{01} = -3.6546 \times 10^7 \) (Pa), \( C_{02} = -4.4964 \times 10^8 \) (Pa), \( C_{03} = -6.0076 \times 10^7 \) (Pa), \( C_{10} = 3.7227 \times 10^7 \) (Pa), \( C_{11} = 7.6055 \times 10^8 \) (Pa), \( C_{12} = 8.5319 \times 10^7 \) (Pa), \( C_{20} = -3.431 \times 10^8 \) (Pa), \( C_{21} = 69,852 \) (Pa) and \( C_{30} = -4,145.2 \) (Pa).
Figure 5.2. (a) Schematic of 3D additive manufacturing process. (b) 3D-printed test sample. (c) 3D-printed actuator.

5.4 Actuator Structural Design

The pneumatic actuator described in this chapter consisted of a series of channels arranged in a row, similar to PneuNets actuators [230, 232, 234]. The structure and working mechanism are shown in Figure 5.1(b). This type of PneuNet can only generate 2D circular bending motions. Normal PneuNets consist of a series of actuation chambers arranged next to each other, with no inclination, as presented in Chapter 4. Compared with normal PneuNets, an optimised chamber structure was used in the actuators considered in this chapter. A series of angled chambers were designed to generate 3D bending and twisting motions (similar to a 3D helix) with more DOF than normal PneuNets. The angled chambers were arranged at a certain degree, parallel to each other. The actuator consisted of two layers, with the upper active layer actuated by input air pressure and a passive bottom layer, as shown in Figure 5.3 (a). When the top layer of the actuator was inflated, the channels expanded, causing the actuator to deform.
in the longitudinal and horizontal direction, as shown in Figure 5.3 (b). By changing the arrangement of the chambers, the deformation and bending shape could be changed, and the combination of different chambers could generate various bending motions.

Figure 5.3. (a) Schematic of 3D helical actuator in its neutral state. (b) Normal bending actuator. (c) 3D helical actuator when activated pneumatically.

5.5. Results

5.5.1 Finite element method modelling

Again, this study employed a finite element model to predict the specific performance of the pneumatic actuator to investigate the effects of primary parameters and optimise
the structure of the actuator. Large deformation effects were taken into account in this model. The helical actuator was fixed at one end and actuated by pressure in each channel. Numerical simulations were conducted to explore the morphological changes in the chamber angle.

![Simulated bending behaviour of helical actuator with chamber angle, $\theta$.](image)

3D FEM models were built for the helical actuators. The thin-walled actuator was analyzed with ANSYS Workbench to simulate the bending and twisting behavior of the actuators under different input pressures. The 3D-modeled geometry in Autodesk Inventor (Autodesk Inc.) was imported to a static structural analysis model in ANSYS Workbench, where the inner connection holes of the inner chambers were not considered, and air pressure was directly applied to all the surfaces of the internal chambers equally. The actuators were modeled with tetrahedron elements and patch conforming algorithm. Fixed support boundary condition was applied to the proximal end of the actuators, which make the actuators act as cantilever beams.
Figure 5.5. (a)(b)(c) Motions on tipping point of helical actuator in x-, y- and z-axes, respectively.
Figure 5.6. (a) Bending angle of helical actuator with different pressure input. (b) Twisting angle of helical actuator with different pressure input.

The simulated bending and twisting behaviors of the actuators under actuation obtained with the FEM models are demonstrated in Figure 5.4. To quantify the angle of bending and twisting motions of the actuators, the motions in X, Y and Z axes at different pressure inputs were obtained through FEM as demonstrated in Figure 5.5 (a-c). As shown in Figure 5.4 (a), the bending angle is the angle between the tangent vector, \( r_t \), and y-axis. Therefore, according to the law of cosines, the bending angle is:

\[
\alpha = \cos \left( \frac{r_t \cdot r_z}{|r_t||r_z|} \right)
\]  

(5.1)
The bending and twisting angles are as shown in Figure 5.6. The motions in the x-, y- and z-axes are demonstrated in Figure 5.6 (a). The calculated bending and twisting behaviours of the actuators under different air pressure obtained through the FEM models are illustrated in Figure 5.6 (b). As the pressure increased, the bending and twisting angles increased. The maximum bending of around 360° bending and twisting could be generated under 50 kPa in the FEM models.

![Figure 5.6](image)

Figure 5.6. Bending and twisting behaviour of the actuators under different air pressures obtained through the FEM models.

5.5.2 Trajectory tracking

The trajectories of the tipping point in the x-, y- and z-directions were recorded using video analysis and a modelling tool (Tracker, Open Source Physics), as shown in Figure 5.7. The results were normalised to the original length of the actuator. The total length of the actuator was 180 mm, and the width was 25 mm. The maximum deformations in
the x-, y- and z-directions were 120 mm, 120 mm and 140 mm, respectively. The experiments were repeated five times, and the average value was recorded as the experimental data. As shown in Figure 5.8, the bending performance of the actuator could be predicted by the simulations. The experimental and simulation results shown in Figure 5.9 indicate that the FEM closely predicted the real twisting behaviour of the proposed helical actuators with different parameters and pressure inputs.

Figure 5.8. Twisting configurations of finite element simulated helical actuator and corresponding real helical actuator under 120 kPa: (a) end view, (b) front view.
Figure 5.9. Experimental and simulation results for tip point of helical actuator under 120 kPa: (a) motion in x-axis, (b) motion in y-axis, (c) motion in z-axis.
5.5.3 Characterisation of helical actuator

The helical actuator was fixed at one end and actuated by a constant pressure. The trajectory of the actuator was estimated by changing the length of the actuator and the angle of the chambers. While the geometry of the chamber was the same, the number of chambers changed as per the actuator length.

A. Effect of chamber angle

This study determined the effect of the range of the chamber angle on the trajectory of the actuator. The chamber angle is one of the main parameters that can affect the trajectory of the actuator. The chamber angle, $\theta$, changed from 0 to 40°. The winding radius, $R$, and pitch length, $h$, both related to the chamber angle. With an increase in the chamber angle, $\theta$, the actuator moved further along the x-axis; the horizontal separation of the helix’s loop, $h$, became larger; the actuator moved less in the y-direction; and the radius of each loop became smaller. Therefore, the winding radius, $R$, became smaller, as shown in Figure 5.10. The motion of the actuator tip was recorded and is shown in Figure 5.11. The tip point moved to the farthest position along the x-axis and then moved back to form a circular shape.

![Figure 5.10. Twisting motion with different chamber angles.](image)
Figure 5.11. Motion of actuator tip point with different chamber angles under 120 kPa.
Actuator has the following dimensions: 120 mm length, 14 mm height and 12.5 mm width. (a) Bending shape related to chamber angle, (b) motion in x-axis, (c) motion in y-axis.
Figure 5.12. (a) Calculated bending angle of helical actuators with different chamber angles, $\theta$, ranging from 0 to 30°. (b) Calculated twisting angle of helical actuators with different chamber angles, $\theta$, ranging from 0 to 30°.

This study calculated the bending and twisting angles with the chamber angle, $\theta$, changing from 0 to 30°. As the chamber angle increased, the bending angle decreased and the twisting angle increased, as shown in Figure 5.12.

B. Effect of length

A helix running around the x-axis is described by the following parametric equation:

\[
\begin{align*}
X(t) &= ht \\
Y(t) &= r \cos t \\
Z(t) &= r \sin t
\end{align*}
\]  

(5.2)

where $t$ is the range of the loops and $r$ is the winding radius.
The helix running around the x-axis is shown in Figure 5.14 (b). With the 500 mm length helical actuator, the winding radius, \( R \), was 10.18 mm, and the range of loops was three. According to the simulation results shown in Figure 5.14 (b), the actuator designed in this study conformed to the helix running around the x-axis, as described by Equation 5.1. When the actuator length changed, the motion in the x-axis and y-axis was nearly the same under the same pressure within the error range allowed.

![Image 1](image1)

1 loop (150 mm)  
2 loops (300 mm)

![Image 2](image2)

More than 3 loops (500 mm)

Figure 5.13. Effect of actuator length on helical configuration of actuator.

![Image 3](image3)

(a)

![Image 4](image4)

(b)

Figure 5.14. (a) Simulation results from ANSYS with helical actuator with 500 mm length. (b) Helix running around x-axis generated using analytical expressions in Equation 5.2.
Figure 5.15. Motion of actuator tip point calculated with simulation results for actuator of length ranging from 150 to 500 mm.

The motion of the tip point along the x-axis and y-axis is shown in Figure 5.15. When the total length was 150 mm, the number of maximum loops that could be generated was only one loop. Limited by the length of the actuator, the maximum bending generated was only one loop. When the length increased to 300 mm, the number of loops increased to nearly two. When the length was 500 mm, more than three loops were generated. Under the same pressure, the expansions of each chamber were the same. Therefore, with the same pressure input when the actuator was sufficiently long,
the winding radius and pitch length of each loop were the same. The length of the actuator did not affect the winding radius and pitch length; it only affected the number of loops that the actuator could create, as shown in Figure 5.13. This indicated that the bending motion of the actuator was a helix with a constant radius and screw pitch.

5.5.4 Blocking force measurements

To measure the force on the tip point exerted by the bending (normal bending actuator generating a two-dimensional trajectory) and twisting (helical actuator) actuators upon different pressure input, the blocking force experiment was conducted using a six-axis pressure sensor (K6D Multicomponent Sensor, ME-Meßsysteme GmbH) to measure the force on the actuator tip.

![Diagram of experimental setup](image)

(a)

![Graph showing blocking force comparison](image)

(b)

Figure 5.16. (a) Experimental setup to measure blocking force. (b) Blocking force comparison of helical twisting actuator (with chamber angle of 30°) and normal bending actuator.
In the experiment, the proximal end of the actuator was fixed on the platform and connected to the pneumatic pressure source, as shown in Figure 5.16 (a). One end of the actuator was connected to the pneumatic pressure source. The other end of the actuator was in contact with the force sensor.

The blocking force measurements were repeated three times, and the average value was used in the results shown in Figure 5.16. The helical actuator with twisting motion could generate a larger blocking force than the conventional bending actuator. The maximum blocking forces recorded were 2.10 N and 1.19 N for the helical actuators and the bending actuators, respectively, under the same pressure of 130 kPa. Thus, the helical actuator was more efficient than the conventional bending actuator.

Figure 5.17. Cross-section of chambers for bending actuator.
The whole actuator which is in the form of a cantilever beam with serial chambers can create bending and twisting movements when actuated. The cross section of the actuator chamber is shown in Figure 5.17. The dimensions of the chambers are kept constant in this analysis and in the simulations and experiments. With reference to Figure 5.18, the cross section or the actuation force \((F=PA)\) will have its projections on the X-Z plane and Y-Z plane, which are

\[
A_{xz}=A \cos \theta \quad \text{and} \quad A_{yz}=A \sin \theta
\]  

(5.3)

The radius of curvature for the actuator deflections in these planes are given in terms of the bending angle \(\alpha\) and twisting angle \(\beta\) in the X-Z plane and Y-Z plane, respectively;

\[
\frac{1}{R_{xz}} = \frac{\alpha}{L} = \frac{PA \cos \theta}{EI} = \frac{PA e}{EI} \cos \theta
\]  

(5.4)
\[
\frac{1}{R_{yz}} = \frac{\beta}{L_t} = \frac{PAe_t}{EI_t} \sin \theta \cos^2 \theta \tag{5.5}
\]

where \(A = ab\) and the corresponding area moments of inertia are given by:

\[
I = \frac{a_0b_0^3 - ab^3}{12} \tag{5.6}
\]
\[
I_t = \frac{b_0a_0^3 - ba^3}{12} \tag{5.7}
\]

and \(L\) and \(L_t\) are the actuator length in the longitudinal and transverse (i.e. in the twisting direction) directions, respectively.

The total angular displacement for the helical actuator is equivalent to

\[
\alpha + \beta = \frac{PAe}{EI} L \cos \theta + \frac{PAe_t}{EI_t} L_t \sin \theta \cos^2 \theta \tag{5.8}
\]

When the chamber angle \(\theta\) is zero, Eq.5.8 gives the bending displacement (i.e. angle) for the normal-angled bending actuator. It must be noted that the deformation of a cross-section under a load depends on its material properties (i.e. modulus of elasticity \(E\)) and geometry (i.e. area moment of inertia \(I\) and \(e\) or \(I_t\) and \(e_t\)). The helical actuator benefits the geometry or configuration of the cross section of its angled chambers to reduce the mechanical resistance to the deformation.

The corresponding blocking forces due to the bending angle \(\alpha\) and twisting angle \(\beta\) can be calculated from\textsuperscript{42}:

\[
F_b = \alpha \frac{EI}{L^2} \tag{5.9}
\]
\[
F_{bt} = \beta \frac{EI_t}{L_t^2} \tag{5.10}
\]

With reference to Equation 5.8 to 5.10, the helical actuator has a higher angular displacement and corresponding blocking force, as supported by the experimental results presented in Figure 5.16(b), than those of the normal-angled bending actuator. This follows that for the same input, the helical actuator outputs a higher mechanical work, i.e., a higher mechanical efficiency than the normal-angled actuator, as presented next.
Figure 5.19. (a) Experiment setup. (b) Simulated blocking force results for helical actuator with same dimensions as helical actuator used for experimental blocking force results shown in Figure 5.16. (c) Arc length of helical actuator with different pressure input. (d) Tangent vectors for space curve. (e) Output work comparison of bending and helical actuators.
The work, $W$, done by a force, $F$, acting on the tip point that moves a distance (arc length, $s$) is produced by:

$$W = F \cdot S \text{ (5.11)}$$

$$F = \sqrt{F_x^2 + F_y^2 + F_z^2} \text{ (5.12)}$$

The trajectory length from a to b, as shown in Figure 5.19 (d), is determined by:

$$W_l = \Sigma^n |c(t_i) - c(t_{i-1})| \text{ (5.13)}$$

$$|c(t_i) - c(t_{i-1})| = \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2 + (z_i - z_{i-1})^2} \text{ (5.14)}$$

The arc length can be calculated using Equations 5.13 and 5.14.

The 3D-modelled geometry for the blocking force test depicted in the top plot of Figure 5.19 was imported to a static structural analysis model, and the actuation pressure was directly applied to all surfaces of the internal chambers. The boundary conditions were the fixed supports at the base of the actuator and the support of the sensor. No separation contact was applied between the bottom surface of the actuator and the top surface of the sensor, similar to the experimental setup in Figure 5.16. The simulation results accurately predicted the blocking force results for the proposed helical actuator, as shown in Figure 5.19 (b). As shown in Figure 5.19 (e), the helical actuator had a higher mechanical work output (or efficiency) than the bending actuator under the same pressure input.

### 5.6. Conclusion

This chapter has described a new SPA consisting of a series of internal chambers with the same helix angle, which can generate bending and twisting motions simultaneously. It has proposed a new bio-inspired, 3D-printed SPA that generates helical (bending and twisting) motions in 3D. The actuator consisted of several angled chambers arranged in a line that could be actuated together using one power source (air pressure). The trajectory of the helical actuator was characterised by changing the angle of the chambers and the actuator length using the FEM. A fully compliant soft helical actuator
was designed and fabricated using 3D printing. This study investigated the bending behaviour of this soft helical actuator. The actuator was characterised by changing its length and the chamber angles using the FEM. The 3D printing method was employed to manufacture the thin-walled, airtight helical actuators directly, without requiring any post-manufacturing process. The printing settings were optimised to print from commercially available material. The blocking force was experimentally measured and numerically calculated. The trajectory of the actuator was recorded, and the blocking force on the tipping point was measured and compared with the corresponding simulation results from the FEM. The behaviours of the helical actuator were compared with those of the actuator with zero chamber angle, but with the same size (i.e., a normal bending actuator generating a two-dimensional trajectory), and the results indicated that the proposed helical actuator had a higher mechanical output (or efficiency) than the bending actuator under the same pressure input.
Chapter 6

Smart Structure Design and Applications

6.1 Introduction

This chapter aims to demonstrate the ability of SPAs to achieve complex movements and develop soft robotic applications, such as bidirectional bending movements, rehabilitation finger applications and soft robotic hand grippers. Based on the comparison of simulation and experimental work in Chapters 4 and 5, the feasibility of designing and optimising smart structures through FEM has been provided. To expand the application of SPAs, this chapter demonstrates different design concepts. Based on this actuation concept, this chapter constructs a four-finger gripper made of the helical actuators and compares its object handling performance with that of a four-finger gripper made of bending actuators (with zero-angled chambers) with the same length. The gripper made of the helical actuator outperforms the gripper of the same size and same input made of the bending actuator when handling objects with various geometries. Further, this chapter constructs another four-finger gripper made of a hybrid actuator consisting of half of the angled chambers and half of the non-angled chambers to demonstrate that the proposed design and fabrication technique could be employed to establish application- and function-specific soft robotic systems.

6.2 Bidirectional Helical Actuator Applications

6.2.1 Design of bidirectional helical actuator

This study’s bidirectional helical actuator consisted of a series of channels arranged in a row. To achieve bidirectional bending, PneuNets were used on both sides. There were two air inlets used for the upper layer and lower layer separately. The structure of the bidirectional helical actuator and the bending motion achieved with this model is shown in Figure 6.1.
6.2.2 Bidirectional motion

To confirm and predict the bidirectional helical motion of this structure, FEM analysis was undertaken. Large deformation effects were taken into account in this model. The bidirectional helical actuator was fixed at one end and actuated by pressure in each channel. The bidirectional actuator was analysed with ANSYS Workbench to simulate the bending behaviour of the actuators under different input pressures. The actuator was set as a cantilever beam with one end set as fixed support. The bending shape with an inflated upper or lower layer is shown in Figure 6.2 (a) and (b) separately, at a similar level of pressure input. It can be seen that the bidirectional helical actuator could achieve helical bending morphology configuration in both clockwise and anti-clockwise directions. It is clear that the bending motions performed in both directions were symmetrical with an inflated upper and lower layer of the actuator when the same pressure input was applied. In addition, by changing the arrangement of the chambers, the actuator allowed bidirectional bending motions.
To characterise the motion of the actuator concerning the variation in the inflation pressure, 10 to 60 kPa pressure inputs were used. The x-direction is the horizontal axis, and y-direction is the vertical axis. The trajectory under different pressure inputs is shown in Figure 6.3. Upon increasing the input pressure, a significant increase in the bending and twisting angle was observed.

Figure 6.2. (a) Configuration with actuated upper layer and (b) actuated lower layer.

Figure 6.3. Trajectory of helical actuator with 0 to 50 kPa positive pressure input.
Figure 6.4. Motions on tipping point of helical actuator in x- and y-axes.

6.2.3 Comparison of positive and negative pressure inputs

Positive and negative pressures were applied to the upper layer chambers equally to attain a better understanding of the actuation methods. Figure 6.5 shows the bidirectional helical motions on the tipping point under applied pressure of 40 kPa and vacuum pressure of -40 kPa. The actuator worked more efficiently under negative pressure inputs, as it reached the most prominent bending configuration earlier than the positive pressure inputs. According to the simulation results, the actuator could afford approximately 60 kPa positive pressure and only 40 kPa negative pressure, as shown in Figure 6.6. However, the structure worked better under the same negative pressure than positive pressure. The structure could achieve more considerable bending and twisting angle under positive pressure due to that it cannot afford the same amount of negative pressure input.
6.2.4 Different designs

To determine an efficient actuator design, different arrangements of chambers were applied based on the bidirectional helical structure. The two-side helical actuator
consisted of two layers of arranged helical actuators, which meant both the upper and lower layers were applied with slant chambers in the same direction. The one-side helical actuator consisted of only one helical actuator, which meant the upper layer was a helical actuator and the lower layer was the normal bending actuator with 0° of chamber angle. The helical actuator was the same typical helical actuator used in Chapter 4. The comparison of the motion of tip points for three different chamber arrangements is demonstrated in Figure 6.7. It can be seen that the two-side helical actuator generated the most considerable bending and twisting performance. As a result of the lower layer chambers, the weight of the lower layer was less than that of the typical helical actuator. The one-side helical structure could bend less because the lower layer bending actuator was limited to the twisting movements of the upper layer helical actuator.

Figure 6.7. Motions on tipping point of three different helical actuators in x- and y-axes.
6.3. Design Concept of Pneumatic Finger to Imitate Hand Function

The function loss of hand and fingers will cause a huge disability and will greatly affect the quality of one’s life. Robot assistive device has been a popular topic for researchers and engineers in the past decades. Duplicating the human hand is one of the most ancient and challenging objectives of robotics research. Over the last few decades, there have been a large number of investigations aiming to achieve this goal, such as prosthetic hands and rehabilitation devices. Prosthetic hand is a kind of mechanical device that can replace a missing hand. A prosthetic hand is supposed to be light and flexible to allow complex movement. Most existing prosthetic hands powered by external energy sources are almost driven by electric motors, such as DC motors. Examples of prosthetic hands deploying these actuators are Belgrade prosthetic hand [256], Tokuji Okada hand [257], Gifu hand [258], Smart Hand [259] and Bebionic hand [260]. The traditional artificial hands are less capable and unsafe for interaction with human beings. Pneumatic actuators are a practical class of actuators for prosthetic hands that are overlooked.

A rehabilitation hand device is an effective method to help patients suffering from motor impairments, especially as a result of stroke, to improve the functions of their hands. After a stroke, the most common symptom is spasticity of the hand, which causes difficulties in the grasping and releasing functions of the hand [261]. Various studies have shown that patients with the help of robot assistance can have a great improvement in hand function recovery [116, 262, 263]. Traditional hand rehabilitation with therapists is not convenient for patients and has relatively high cost [263]. The human hand is a complicated instrument consisting of 29 skeletal muscles, which can provide 21 DOF [264]. Imitating the human hand is one of the most challenging problems in robotics research, and, over the last few decades, there have been a large number of approaches aiming to solve this problem. The capability of a rehabilitation hand dramatically depends on the performance of the actuation method. A rehabilitation glove can help patients who suffer from hand injuries and diseases such as stroke to improve the functions of their hand. Hand function recovery requires long-term assistive training; therefore, it is necessary to develop a convenient rehabilitation glove with a simple structure and control method that can be used by the patients themselves.
In Chapter 4, the structure of the pneumatic actuator was optimised and redesigned according to the FEM results. The current chapter aims to imitate the real human hand both in working mechanism and appearance. Several channels are arranged at two joints to achieve bending. In the first configuration, shown in Figure 6.8, the actuator has two series of chambers, and, between the two series, there is a gap without chambers to allow a finger-like bending shape. The same size of channels is used in the finger. The bending shape is not a circle. Therefore, this configuration is useful in the imitation of the human hand bending shape.

![Figure 6.8. Actuator with two series of chambers that has a gap without chambers.](image)

The optimised design of the actuator is shown in Figure 6.9. The channels are larger at the bottom and become smaller towards the fingertip. The channels are larger at the fixed end and become smaller at the tip. Moreover, the improved appearance is more like a real human finger.
Imitation of finger appearance is easy, yet it is very difficult to imitate the complex motive functions of a human hand. To obtain similar bending motions with a real finger, this study separated the channels into three parts. When controlled separately, each joint could bend 90°. The length of each finger on a real hand is different; thus, the total length of the finger was designed to be able to achieve different functions. Considering the feasibility of fabrication and simulation results, the wall thickness of the optimised design was set as 1 mm.
If the joints are controlled separately, the flat pinch and fingertip pinch functions can be realised. Moreover, an actuator that can extend in one fixed direction can help achieve finger spread function. The channels are controlled separately to generate various finger configurations to achieve grasping targets with various shapes. When different pressures are applied to the joints, the corresponding deformation will differ—the actuator can bend like a circle to grasp a round object, such as a cup, and can generate an elliptical shape to pick up an object such as a pencil.

Figure 6.11. Bending shape under different input pressures.
6.4. Applicability: Multi-finger Soft Robotic Grippers

Based on the design and fabrication method in Chapter 5 and combining the design and optimisation methods in this chapter and Chapter 5, an entire soft helical actuator with 180 mm in length was designed and fabricated, where a pressure of 160 kPa generated by a miniature pump was applied to grasp a syringe (like plant tendrils), as shown in Figure 6.12.

![Control unit](image1)

(a)

![3D-printed actuator](image2)

(b)

Figure 6.12. (a) Helical configuration of actuator. (b) One single helical twisting actuator used as a one-piece gripper to handle a cylindrical object.
The four-finger gripper was used to grasp various objects, such as cylindrical cups, rectangular boxes, injection syringes, irregular tubes, knives, scissors and pliers, as illustrated in Figure 6.15. This gripper was activated with a pressure of 120 kPa to grasp some irregularly shaped objects, shown in Figure 6.15, which were difficult to grasp and lift using the four-finger gripper made of four bending actuators with zero chamber angle. With the increase in the contact area and effective working length, the helical gripper could hold cylindrical objects, which could not be grasped and lifted by the four-finger gripper made of four bending actuators with zero chamber angle. The actuator bent into a helical shape similar to that of the aforementioned simulation results. The helical trajectory could be observed through the grasping experiments. The grippers could be adjusted to work effectively with complex objects by changing the pressure, geometry of the chambers and arrangement of the chamber angle. The
simulation for a multi-finger starfish gripper is shown in Figure 6.14, which indicates the possibility of making a multi-finger soft robotic gripper with one input pressure. With larger contact areas and more complex configurations than the ordinary bending actuator, the helical actuator can provide a more efficient grasping capability, especially with irregularly shaped objects. The gripper failed to grasp a tennis ball. To remedy this, a four-finger gripper made of actuators with a combination of chambers (half with 0° and half with 30°) was constructed, as shown in Figures 6.13 (b) and 6.15, to hold the tennis ball. An actuator with such a combination of chambers could generate more configurations and perform more complex tasks. It follows that the proposed method could be employed to build active structures (fingers) for a specific application and function. Thus, this study contributes to the efforts towards building function-specific soft robotic systems.

Figure 6.14. Bending shape of a starfish-like multi-finger gripper.
Figure 6.15. Four-finger gripper grasp experiment.
6.5. Conclusion

This chapter has developed a novel bidirectional helical actuator, pneumatic finger and multi-finger soft robotic gripper to expand soft robotic applications. Nonlinear FEM analysis was used to derive the motion of the design concepts. The novel bidirectional actuator could generate a symmetrical twisting motion with two air-supply sources. The efficiencies of the negative and positive input pressures were compared. Moreover, different arrangements of the chambers were applied to gain a better understanding of the bidirectional helical actuator. This design has the potential to be used in various soft robotics applications, such as grippers to grasp delicate and complex objects.

This chapter also demonstrated a design concept of a pneumatic finger that sought to imitate the configuration of a real human hand. The channels were controlled separately to generate various finger configurations to achieve grasping targets with various shapes, like human hands. After modelling, the fabricated actuators were demonstrated as a gripper to grasp objects with various shapes. Based on the design and fabrication methods demonstrated, a four-finger gripper based on the proposed helical actuator was fabricated and used to grasp and lift complex shapes, which could not be grasped and lifted by the bending actuators with zero chamber angle. Further, another four-finger gripper made of a hybrid actuator consisting of half angled chambers and half non-angled chambers was constructed to demonstrate that the proposed design and fabrication technique could be employed to establish application- and function-specific soft robotic systems.
Chapter 7

Conclusions and Future Work

7.1 Conclusions

This thesis has examined the current development and promising potential of pneumatic actuators as flexible fluidic actuators for undertaking complex tasks in soft robotic applications. The primary objective of this project was to establish a pneumatic actuation system with a specific function for soft robotic applications. The aims of this project were achieved through the work presented in this thesis and are concluded below:

- With analytical and experimental approaches, as well as computational studies, the pneumatic actuator was modelled as a soft robotic actuator to be used in various applications.

- The hyperelastic materials used to fabricate the soft actuator were characterised. In the experimental study, the stress–strain behaviour of soft materials M4601, Ecoflex 00-10, soft translucent silicones and FilaFlex were studied using a uniaxial tensile test system. In the simulation study, to determine a strain energy function for nonlinear hyperelastic materials, a comprehensive comparison of seven available hyperelastic models was conducted through finite element analysis. The Mooney-Rivlin model showed potential to be used to characterise hyperelasticity in FEM because of its excellent match with the experimental stress–strain data under large deformation. The material constants for the nonlinear soft materials were calculated for further use in numerical studies.

- The performance of a bending pneumatic actuator with discrete chambers was optimised. A study of the essential design parameters was conducted through FEM. The effects of various design parameters—including the operation pressure, wall thickness, gap between chambers, bottom layer thickness and geometry of the channel cross-section—were studied. ANOVA analysis was performed to systematically determine which actuator parameters affected the
deformation or bending angle of the actuator significantly. The optimised design of bending pneumatic actuator was fabricated after the simulations. Moreover, experimental tests were undertaken to quantify the performance of the actuator. The simulation and experimental results were compared and analysed. An optimisation method was proposed, which can be extended to the design of flexible fluidic actuators to enable more complicated structural designs.

- A new bio-inspired, 3D-printed helical (bending and twisting) SPA with angled chambers arranged in a line was designed and optimised. The low-cost FDM technique was used to fabricate the helical actuator directly with the nonlinear material FilaFlex, which was selected as the printing material for its high elasticity and excellent abrasion resistance. Using a commercially available FDM 3D printer, the printing settings and extruding unit were optimised to directly print the thin-wall (0.64 mm) airtight 3D helical structure without any post-manufacturing process.

- The trajectory of the helical actuator was characterised by changing the essential design parameters to gain a better understanding of the bending and twisting behaviour. The blocking force was measured both experimentally and numerically for helical actuators and those of the actuator with zero chamber angle (traditional bending actuator). The results were compared and studied. Compared with the bending actuators with only circular bending motions, but the same size, the proposed helical actuator had higher efficiency under the same pressure input.

- Different design concepts—such as a bidirectional bending actuator, rehabilitation finger application and soft robotic hand gripper—were developed to expand the applications of SPAs. A fully compliant soft gripper with four fingers made of helical actuators was experimentally demonstrated. The four-finger gripper was used to grasp and lift objects with complex shapes, which could not be achieved by the normal bending actuators. Another four-finger gripper with hybrid actuators was constructed. The proposed design and fabrication methods could be used to establish application- and function-specific soft robotic applications.
7.2 Future Work

Given that flexible fluidic actuators have a broad range of application areas, a few possible future avenues of research derived from this study can be suggested:

- In this research, experimental and computational study was conducted. Further interpretation of a kinematic model of the optimised design using transformation matrices for the SPAs may be considered to gain further insight into the kinematic behaviour of the actuators and the mechanisms that they articulate.

- The direct 3D printing of soft hyperelastic materials was achieved by FDM method. This technique is believed to be suitable for various hyperelastic materials, where a wide range of applications may be created. Further studies may be undertaken to explore more suitable hyperplastic materials with different stiffness and to improve the resolution of 3D printing technique to gain more applications of soft printable actuators. Novel mass production methods for soft robotic actuators will be considered to improve the efficiency.

- As described in Chapter 6, several interesting applications (such as the finger and bio-inspired starfish gripper) may be fabricated after optimisation for rehabilitation gloves, soft grippers and agricultural and undersea robotic applications. Future research may develop different designs with various arrangements of chambers that can generate the required bending motions. Optimisation-function-structure-fabrication processes should simultaneously be considered to result in application-specific actuators. In future design, both the positive and negative actuation pressure methods will be considered to actuate different structures with complex design specifications. This will help broaden the applications of these actuators.

- The position control of these SPAs may be improved by using 3D-printable flex sensors to enhance the control of their motions, thereby better meeting the performance requirements of their applications. Soft sensors indicate their potential for soft robotic applications, especially for medical and surgical
devices. A highly compliant 3D-printable soft sensor that can provide multi-modal sensing will be highly desired.

- In this study, the pneumatic actuators were powered by a miniature pump and a microcontroller. A more portable control system with a smaller footprint and smarter controller—such as electromyography sensors—could be designed and improved to attain a smarter control system for soft robotic applications, which is especially meaningful for hand rehabilitation and prosthetic hand applications.

- Design optimisation and fabrication of this actuation concept may be extended to micro-sized applications, which may be used in medical applications and even in microinvasive surgery.
References


References


References


References


References


References


The publications related to this work are as follow:


Patents:
