The Development of Artificial Muscles Using Textile Structures

A thesis submitted to The University of Manchester for the degree of Doctor of Philosophy in the Faculty of Engineering and Physical Sciences

· 2010 ·

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17
Abstract

The University of Manchester
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Doctor of Philosophy
The Development of Artificial Muscles Using Textile Structures
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The aim of this project was to investigate the use of textile structures as muscles to assist people with muscular deficiency or paralysis. Due to the average life expectancy continuing to increase, support for those needing assistance to move unaided is also increasing. The purpose of this project was to try to help a patient who would normally need assistance, to move their arm unaided. It could also help with rehabilitation of muscular injuries and increasing strength and reducing muscular fatigue of manual workers.

The approach considered was to develop an extra corporal device for the upper limbs, providing the main required motions. Most devices currently available use motors and gearboxes to assist in limb movement. This study investigated a way of mimicking the contraction of biological skeletal muscles to create a motion that is as human as possible with a soft, flexible and lightweight construction.

Electroactive polymers (EAPs) and pneumatic artificial muscles (PAMs) were investigated. It became clear that at present, the EAPs were unable to create the forces and speed of contraction required for this application. The use of pneumatics to create artificial muscles was developed upon. PAMs, like the McKibben muscle and the pleated pneumatic muscle mimic the natural contraction of skeletal muscle. These current PAMs were used as a basis to develop a new type of pneumatic artificial muscle in this project. A 90 mm ball-like structure was developed, produced from an air impermeable rubber coated cotton fabric. Joining three oval panels together created a 3-D spherical shape. Three of these structures were linked together, and when inflated, created an acceptable level of contraction and force. This method of producing artificial muscles created a soft, lightweight and flexible actuator with scope for different arrangements, sizes and positions of the muscle structure. The contraction process was mathematically modelled. This calculated the predicted rate and level of contraction of a 2-D muscle structure. These mathematical findings were able to be compared to the practical results, and produced similar contraction characteristics.

The muscle structures were incorporated into a garment to form a type of muscle suit which could be worn to assist movement. This garment has an aluminium frame to protect the wearer’s bones from stresses from the contracting muscles. This study has shown that the muscle suit developed can create movement for wearers that would normally need assistance, and also reduce muscle fatigue, which would be useful for manual workers. This is incorporated into a functional and wearable garment, which is easy to dress and more lightweight and aesthetically pleasing than current muscle suits.
Declaration

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Acknowledgments

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Finally I would like to extend a special thanks to my family and friends. It has been a long journey but their support and faith has been never ending.
Chapter 1

Introduction

In a society with ever improving social welfare and healthcare, the population is living to an older age. This leads to an ever-increasing number of elderly people with limited mobility and strength who may require assistance to cope with daily activities while still retaining their independence. This situation has been the basis for this project. The aim was to create a wearable, textile-based device, capable of assisting the movement of the wearer’s arm.

Two main areas for study in this project were identified. They were: the study of the actuator which would produce the movement, and the incorporation of this into a wearable garment. In order to find a suitable actuator, the human muscle was studied, as it is this muscle’s function that any artificial muscle created in this project was trying mimic. There were found to be two types of actuator potentially suitable for this project. The first studied was electroactive polymers (EAPs). EAPs are polymers, which are able to respond to electrical stimuli and significantly change shape or size with movements that can induce large strain [15]. The earliest EAP can be traced back to 1880 [15], but it has been only in the last 20 years that they have become advanced enough to be used in applications such as a swimming toy fish, drug release capsules and on a spacecraft [32]. Despite there being many different types of EAPs in production, currently none of these were appropriate for use in this application. The slow contraction and relaxation speed, limited force created, and concerns over the high voltages required for the contraction of some EAPs made them unworkable. The next actuator option was pneumatic artificial muscles (PAMs). PAMs are generally a cylindrical or spherical membrane which when inflated expand radially and contract axially. This generates a pulling force along the longitudinal axis [71]. The PAM
can be dated back to a 1930 design by a Russian inventor named Garasiev [25]. Since then there have been numerous designs and developments on the PAM concept. Several types of PAM are discussed, from the historical to the novel and to the efficient modern day designs. Research into the area of PAMs showed that they would be the most suitable for this project, due to their good power to weight ratio, and their fast response time. Currently, there is no PAM made entirely from textiles. As this project would require the combining of an actuator into a textile garment, it seemed sensible to try to create a PAM also made from textiles. This would create a soft, flexible and lightweight actuator which would combine well with a textile garment to create an aesthetically pleasing and easy to wear garment.

The use of actuators to help with mobility is not a new concept. The area of wearable actuator driven orthotics, or “muscle suits” is discussed in this work. The incorporation of a PAM into orthotics can be dated back to the 1960’s, where a PAM was used to help persons with severely paralysed hands to create a three fingered pinch [54]. Since the 1960’s several other wearable orthotic devices have been developed; most notably, Kobayashi’s muscle suit. The initial concept of this muscle suit was to directly sew PAMs into a jacket to aid movement. Testing showed that this was not a functional method, so a frame was incorporated. The most recent design of this muscle suit created a large and bulky, armour-type suit. Although this does allow the wearer to realise seven upper limb motions, it looks bulky and possibly uncomfortable. In order to create a less bulky and more easy to wear suit, a new type of PAM was created for this project. This PAM was made totally from textiles. Several stages of design, development and testing were carried out before settling on the final design. The stages of design are discussed in this thesis along with the methods of production developed to create this 3-D, air-tight structure. The PAM was capable of creating reasonable levels of force and contraction.

The PAM developed was tested to measure the amount of contraction created when being inflated at different pressures and whilst lifting various loads. This was also modelled mathematically. This model calculated the shape and curvature of the muscle structure that would be created under specified loads and pressures and these theoretical predictions could be compared to the actual results.

In a different approach to other muscle suits, the method of attaching the actuator to
the wearer’s body was influenced by how prosthetic arms are attached to amputees. This allowed for a solid but comfortable foundation for the attachment of a frame and PAMs to the body. A textile jacket was created around the frame and PAMs. This was a two-layered jacket, so there was no contact between the wearer’s skin and the frame or PAMs. This also created an aesthetically pleasing garment which outwardly shows no obvious signs of what is underneath. The jacket created is flexible, soft and lightweight due to being textile based, with a total weight of $1.2 \text{ Kg}$. The muscle suit created in this project was tested for its functionality. The amount of contraction it was able to create, whilst lifting various loads was measured, the speed of contraction was measured, and finally an evaluation of wearer fatigue was carried out.

1.1 Thesis Layout

Chapter 2 covers background research and a review of literature in this field. A brief study of biological muscles was undertaken to see how muscles function. Once the mechanics of the human muscle were understood, a study of the current methods of mimicking muscle function was undertaken. The methods covered are electroactive polymers and pneumatic artificial muscles. A full discussion on the various types of each is included.

Chapter 3 discusses the current status of muscle suits that have been, or are currently in development or production.

Chapter 4 describes the early development stages of a new type of pneumatic artificial muscle. Various designs were tested to find the shape with the highest level of contraction. This design was developed to find a suitable material to create it from and the challenge of creating an air-tight seal is described.

Chapter 5 shows the results from testing this prototype muscle structure. The amount of contraction and the change in circumference whilst the muscle structure was bearing different loads was recorded and the results are discussed.

Chapter 6 describes the further development of the muscle structure. The muscle structures were made smaller and linked in series. Several stages of testing and development are discussed, and the final design of the muscle structure is shown.

Chapter 7 presents the mathematical modelling of the muscle structure. Several stages are described up to the final model, which was compared to the actual testing results and the
comparison of results discussed.

Chapter 8 describes the construction of the muscle suit. The stages of designing and creating the harness and frame are described, and the incorporation into the final garment.

Chapter 9 covers the testing of the muscle suit. Angular contraction, speed of response and fatigue reduction were all tested and discussed.

Chapter 10 concludes the findings of the work and discusses recommendations for further work.
Chapter 2

Background Research and Review of Literature

As the aim of this project was to create an artificial muscle capable of augmenting the movement of a human arm, it was therefore important to understand how a human muscle functioned. The first section of this chapter studies how movement is created by a human muscle. The next sections focus on how to mimic this movement. First, using electroactive polymers, and second using pneumatic artificial muscles. A conclusion was then drawn about which method would be best suited for this project.

2.1 Biological Muscles

2.1.1 Introduction

The human body creates movement with the use of bones and muscles. To create movement and locomotion, the bones are moved by the alternate contraction and relaxation of muscles. Muscle accounts for about 40% of human body mass. The contractions of these muscles generate the stability and power for all human movement [16], voluntary and involuntary. It is beyond the scope of this work to give a detailed description of the workings of muscles, but their characteristics and basic principles need to be discussed as a type of actuator.
2.1.2 Types

The human body contains more than 430 muscles, which can be classified into two types; smooth and cross striated [29]. In invertebrates, the cross striated muscle class contains two different types of muscle; cardiac and skeletal. The smooth or unstriated muscle class contains only one type of muscle, which is used for the internal control of the gut, blood vessels and the viscera [75]. While the fibres are essentially the same for each of the types of muscle, the way that they are arranged is different.

Smooth or Involuntary Muscle

Smooth muscle lines the walls of the hollow viscera and vessels of the body and is responsible for their contraction, usually by peristalsis. In vertebrates, smooth muscles are composed of fusiform cells (tapered at both ends like a spindle) each with a single nucleus and faint longitudinal striations. In a relaxed state each cell is generally 25 - 50 µm long and 2 - 10 µm in diameter. The arrangements of the cells are as sheets or bundles [75]. Figure 2.1 shows the longitudinal cross-section of smooth muscle.

Although the structure and arrangement of smooth muscle varies greatly from that of skeletal muscle, it can develop an isometric force per cross-sectional area that is equal to that of skeletal muscle. However, the speed of smooth muscle contraction is only a small fraction of that of skeletal muscle. The vertebrate does not consciously control the movement of smooth muscle. It is primarily under the control of the autonomic nervous system [30].

Figure 2.1: Longitudinal Cross-Section of Smooth Muscle [48]
Cardiac Muscle

Cardiac muscle is a type of striated muscle, which is found only within the heart. Like smooth muscle, the contraction of the muscle cannot be voluntarily controlled. It is myogenic, meaning that it stimulates its own contraction without requiring an electrical impulse from the nervous system. Specialised pacemaker cells in the heart send out electrical impulses through the muscle tissue and the cardiac muscle cells stimulate their neighbouring cells to contract and so rhythmically pump blood throughout the body. The cardiac muscle cell contains one nucleus located near the centre; adjacent cells form branching fibres that allow the nerve impulses to pass from cell to cell [59]. The longitudinal cross-section of the cardiac muscle can be seen in Figure 2.2.

![Figure 2.2: Longitudinal Cross-Section of Cardiac Muscle](48)

Skeletal Muscle

Skeletal muscle is striated and it is the predominant muscle type in the vertebrate body. This can be seen in Figure 2.3. With humans having approximately 400 skeletal muscles, they make up the majority of the 40% mass which muscle contributes to the overall human composition. Skeletal and cardiac muscle can contract by up to 30% [29]. As the skeletal muscle is the muscle that this project is most interested in mimicking, further discussion will concentrate on the function and anatomy of this type of muscle.
2.1.3 Anatomy

Muscle is composed of a protein called actomyosin. Along with the requisite artery and vein for the supply of oxygen and energy, and removal of waste products, and a nerve supply to allow the contraction to be controlled by the central nervous system, muscle consists of approximately 80% water [75].

The basic structure of muscle consists of muscle fibres, possibly hundreds or thousands, which are arranged in bundles called fascicles bound by connective tissue. Together they
form the typical fusiform shape. The anatomy of a skeletal muscle is shown in Figure 2.4. Each muscle fibre is a long cylindrical cell with multiple oval nuclei arranged underneath its membrane called the sarcolemma [52]. This unique arrangement of the nuclei allows for high efficiency. The muscle fibre itself is composed of bundles of myofibrils [36]. These are composed of bundles of myofilaments, which are a series of even smaller units called sarcomeres. It is the very orderly arrangement of the protein filaments of actin and myosin in the sarcomeres into distinct bands, which gives the striated appearance to the muscle [52].

The strength of skeletal muscle is directly proportional to its cross-sectional area. Most skeletal muscles are attached at each end to a connective tissue (tendon, ligament, aponeurosis or fascia), to a bone or cartilage, or to an organ or to the skin [30]. They usually have one end, known as the origin, which is attached to a relatively stationary bone, (such as the scapula) and the other end, the insertion, which is attached across a joint, to another bone (such as the humerus). On contraction of the muscle, the tendon transfers the contraction force to the skeleton as torque acting on a joint [36].

### 2.1.4 Contraction Process

Muscles work like a biological machine. They convert chemical energy, derived from food, into force and mechanical work. This energy must be continually expended in order to be converted into force. The fuel used by muscles is adenosine triphosphate (ATP) [75].

The term “contraction” is used to describe the tension-developing response of a muscle to a stimulus [30]. The contraction process, shown in Figure 2.5, begins with a nerve impulse from the central nervous system. The muscle cells are stimulated by acetylcholine, which is released at neuromuscular junctions by motor neurons. The actin filaments are pulled along the myosin filaments, requiring the fuel of ATP. The bands of proteins are pulled closer together, causing the sarcomere to shorten. Although the difference in length produced by one sarcomere contracting is negligible, when a few thousand along the length of the muscle do so, there is considerable shortening of the muscle [22].
2.1.5 Antagonism

It is very rare that a single muscle will contract by itself. A whole set of muscles will contract in sequence to produce movement. As muscles can only pull and not push, to gain full range of motion muscles tend to work in pairs. The two muscles, which create opposite movement, are called antagonistic pairs. The muscle, which is regarded to produce the main movement, is called the agonist or prime mover. The muscle, which produces the opposite movement, is called the antagonist [30]. The muscles in the upper limb are a good example of antagonism, as shown in Figure 2.6. At the front of the arm is the biceps muscle. The upper end of the biceps muscle is attached to the scapula by means of two tendons. These points of attachment are the origin of the biceps as they are fixed. The lower end of the biceps is attached to the radius of the forearm. The radius is moved upwards as the biceps contracts. Because movement is brought about at this end of the muscle, this point of attachment is the insertion [6].

The muscle antagonistic to the biceps is called the triceps. It is situated at the back of the arm, just behind the humerus. The origin of the triceps consists of three tendons. One
is attached to the scapula and the other two are situated to the back of the humerus. The point of insertion is situated at the end of the ulna, just behind the elbow joint. The arm is flexed by the contraction of the biceps muscle, which becomes shorter and thicker. The triceps muscle relaxes and becomes longer and thinner as the biceps contracts and the arm bends at the elbow. The arm is extended by the contraction of the triceps and the relaxation of the biceps [6].

![Antagonistic Muscle Control in the Upper Limb](image_url)

Co-ordinated movements and precise control of the degree of flexion and extension are achieved by varying the tension between the antagonistic set of muscles. When the body is at rest the antagonistic muscles remain in a state of tension or tone and so hold the body in position in order to maintain the correct posture [6].

### 2.1.6 Muscle Strength

The following tables (2.1 and 2.2) exhibit the force exerted by the elbow on flexion and extension. This information can be interpreted as the strength exerted by the biceps and triceps on contraction and relaxation when raising and lowering the hand to the shoulder. They show that depending on gender and dominance of the arm, the range that the biceps and triceps can exert is between 16.56 – 37.87 Kg. As this is the arm strength of a healthy
adult, any artificial muscle used should aim to be able to lift $16 \, Kg$ at least.

<table>
<thead>
<tr>
<th>Elbow Flexors</th>
<th>Force in Kilograms</th>
<th>Force in Newtons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Women</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dominant</td>
<td>23.45</td>
<td>229.97</td>
</tr>
<tr>
<td>Non-Dominant</td>
<td>22.86</td>
<td>224.19</td>
</tr>
<tr>
<td><strong>Men</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dominant</td>
<td>37.87</td>
<td>371.43</td>
</tr>
<tr>
<td>Non-Dominant</td>
<td>36.51</td>
<td>358.08</td>
</tr>
</tbody>
</table>

Table 2.1: Force Exerted by Flexion of the Elbow
[11]

<table>
<thead>
<tr>
<th>Elbow Flexors</th>
<th>Force in Kilograms</th>
<th>Force in Newtons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Women</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dominant</td>
<td>16.56</td>
<td>162.36</td>
</tr>
<tr>
<td>Non-Dominant</td>
<td>17.51</td>
<td>171.70</td>
</tr>
<tr>
<td><strong>Men</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dominant</td>
<td>26.40</td>
<td>258.89</td>
</tr>
<tr>
<td>Non-Dominant</td>
<td>27.53</td>
<td>270.01</td>
</tr>
</tbody>
</table>

Table 2.2: Force Exerted by Extension of the Elbow
[11]

### 2.1.7 Conclusion

This section has shown what needs to be replicated by an artificial muscle. Two methods are currently being used to mimic the human muscle. As previously stated these are the electroactive polymer and the pneumatic artificial muscle. The next sections discuss the production and uses of these. A discussion of the practicality of incorporating these into this project is also included.
2.2 Electroactive Polymers

2.2.1 Introduction

The beginning of the field of electroactive polymers (EAPs) can be traced back to an 1880 experiment conducted by Roentgen using a rubber band that was charged and discharged with a fixed end mass attached to the free end. It has only been in the past 20 years, new polymers have been produced which have been able to respond to electrical stimuli and significantly change shape or size with movements that can induce large strain [15]. They can be described as materials, which can bend, twist, stretch or contract when stimulated by an electrical charge. Applications already include a swimming toy fish, drug release capsules and a windscreen wiper for the optical / infrared window of the palm sized Nanorover which was planned to travel as part of a mission to an asteroid in 2005 [32].

These EAPs respond in a similar fashion to biological skeletal muscles, so they have been termed artificial muscles. This characteristic makes them of particular interest to those in the biomimetics field, as it is foreseeable that these materials may be applied to mimic the movements of animals, insects and even human body parts [14]. EAPs are able to replace electric motors with smaller, lighter and cheaper actuators [12]. These new polymers have many advantages over the older electroactive ceramics and shape memory alloys. Compared to the rigid and fragile electroactive ceramics, EAPs can induce a strain, which are two orders of magnitude greater. EAPs have a faster response time, lower density and greater resilience than shape memory alloys. The current limitations of EAPs include low actuation force, mechanical energy density and robustness [15].

EAPs have been divided into two main groups, based on their actuation mechanism. These are electronic, which are driven by an electronic field or Coulomb forces and ionic, which involve the mobility or diffusion of ions. Electronic polymers (electrostrictive, electrostatic, piezoelectric and ferroelectric) require high activation levels \( >150 \, \text{V/\mu m} \). They can hold induced displacement under activation of a DC voltage, allowing them to be used in robotic applications. They have a greater mechanical energy density. Unlike ionic EAPs, electronic EAPs can be operated in air [12].

Ionic EAPs (gels, polymer-metal composites, conductive polymers and carbon nan-
Electroactive Polymers

2.2 Electroactive Polymers

otubes) require lower drive voltages, as low as 1–5 V [15] so they are able to run directly off batteries. If the current is on, the EAP will keep moving. Disadvantages of ionic EAPs include the need for them generally to be wet. This means they have to be sealed in flexible coatings and if the voltage rises above a certain level, electrolysis may occur which will cause irreversible damage to the material [12].

There is another type of polymer actuators, which are non-electrically deformable polymers. These polymers can change shape or volume due to repulsive intermolecular forces that expand the polymer network, and attractive forces that shrink it. Repulsive forces are electrostatic or hydrophobic and the attractive forces are hydrogen bonding or Van der Waal’s forces. The competition between these forces can be controlled by a solvent or gel, pH, magnetic fields, temperature or light [15].

2.2.2 Electronic Electroactive Polymers

Ferroelectric Polymers

Ferroelectric Polymers are controlled by piezoelectricity. Piezoelectricity was discovered in 1880 and occurs when certain crystals, notably quartz, tourmaline and Rochelle salt, are compressed along certain axes and a voltage is formed on the surface of the crystal. In reverse, the application of an electric current causes the crystals to sustain an elongation (Pierre and Paul-Jacques Curie). It is called ferroelectricity when a non-conducting crystal or dielectric material exhibits spontaneous electric polarisation. The most widely used polymers are Poly (vinylidene fluoride) known as PVDF or PVDF2 and its copolymers, which consist of a partly crystalline component with an inactive amorphous phase.

When a large AC field (∼200,000 V/µm) is applied, it can induce electrostrictive (non linear) strains of nearly 2%. This level of AC field is very close to dielectric breakdown, and the dielectric hysteresis (loss, heating) is very large. Ferroelectric EAP actuators can be operated in air, vacuum or water and over wide temperature ranges [15], [14].
Electrets

Electrets were discovered in 1925. Like ferroelectric polymers, electrets also exhibit piezoelectric behaviour. They consist of a geometrical combination of hard and soft layers with non-conventional routes for symmetric breaking.

They are able to retain their electrical polarisation after being subjected to a strong electric field. Positive and negative charges in the material are displaced along and against the direction of the field. This produces a polarised material with zero charge. Electrets can be produced from polymers, ceramics and some waxes. Uses include electrostatic microphones [15].

Dielectric EAPs

Polymers, which have low elastic stiffness and high dielectric constant, can be used to induce large actuation strain when subjected to an electrostatic field. This type is also known as electrostatically striccted polymers (ESSP).

Dielectric EAPs require high electric fields (∼100 V/µm) and can induce significant strain levels (10 – 200%). The associated voltages are close to the breakdown of the material. A disadvantage of this type of EAP is that it is too stiff to be used as an actuator at low temperatures [15].

Electrostrictive Graft Polymers

These are polymers which consist of two components, a flexible backbone macromolecule, and a grafted polymer that can be produced in a crystalline form. The material has a high electric field induced strain (∼4%) combined with a relatively high electromechanical power density and excellent processability.

Electrostrictive graft polymers can be operated as a piezoelectric sensor or an electrostrictive actuator. The actuator is able to bend in both directions under controlled electric field excitation [15], [14].
Electrostrictive Paper

As the process of making paper uses various mechanical processes, with chemical additives it is possible to create a paper with electrostatic properties. An electrostrictive paper EAP has been developed by bonding two silver laminated papers with silver electrodes placed on the outside surfaces. When an electric voltage is applied to the electrodes, a bending displacement occurs. These actuators are lightweight and simple to fabricate [15].

Electroviscoelastic Elastomers

These types are composites of silicone elastomer and a polar phase. In an uncured state, they behave as electrorheological fluids. During curing an electric field is applied which orientates and fixes the position of the polar phase in the elastomeric matrix. An applied electric field ($< 6V/\mu m$) induces changes in the shear modulus [15].

Liquid Crystal Elastomer (LCE) Materials

LCEs have piezoelectric characteristics and are electrically activated by Joule heating. They are composites of monodomain nematic LCEs and conductive polymers. Their actuation mechanism involves phase transition between nematic and isotropic phases over about 1 second. The reverse process takes considerably longer at about 10 seconds.

Researchers at the US Naval Research Laboratory are developing LCE actuators, which have performance properties similar to biological muscles. A monomer with low nematic–isotropic transition temperature, which has ease of alignment, is being sought. Two backbones being considered are Polyacrylate and Polysiloxane [15].
2.2.3 Ionic Electroactive Polymers

Ionic Polymer Gels (IPG)

Polymer gels can be synthesised to produce actuators, which can match the force and energy density of biological muscles. The material, generally polyacrylonitrile, is activated by a chemical reaction. A change from acid to alkaline conditions causes the gel to become dense or swollen, respectively. The response time of this material is slow due to the diffusion of ions through the multilayered gel. The shrinking of a layered gel from 6 x 6 cm to 3 x 3 cm can take about 20 minutes. Non-ionic polymer gels containing a dielectric solvent can be made to swell under a DC electric field under significant strain [15], [14].

Ionic Polymer Gels used in McKibben Style Actuators

Bertrand Tondu and his team from the University of Toulouse, France have been investigating the incorporation of IPG into a McKibben style actuator. The McKibben muscle, which is described in more detail in the following pneumatic artificial muscle section, traditionally consists of a rubber bladder covered by a braided nylon shell. The muscle is traditionally pneumatically driven. The compressed air causes the internal bladder to expand and contract and the braided shell restricts the bladder from over expanding. Tondu has experimented using IPG as a replacement for the compressed air in the bladder. Polyacrylonitrile filament gel fibres were used, which expand and contract with the introduction of sodium hydroxide and hydrochloric acid irrigation. This contraction results in the shortening of the McKibben muscle, which creates a pulling force. Figure 2.7 shows the experimental set-up. Results have shown that forces of up to 64 N can be created. The disadvantage of the IPG to replace compressed air to actuate a McKibben style muscle is the slow contraction speed. To reach a force of 64 N, a time of over 30 minutes was required. The concentration of the NaOH and HCl contribute to the speed of the contraction. The higher the concentration, the faster the reaction and the greater the generated force [70].
Ionomorphic Polymer-Metal Composites (IPMC)

This is a type of EAP, which bends in response to an electrical activation as a result of mobility of cations in the polymer network. Two types of base polymer are used to form IPMCs. These are Nafion® (perfluorosulphonate manufactured by Du Pont) and Flemion® (perfluorocarboxylate manufactured by Asahi Glass, Japan). IPMC require relatively low voltages to stimulate a bending response (1 – 10 V) with low frequencies below 1 Hz [15], [14].

Conductive Polymers

Conductive polymers typically actuate via the reversible counter-ion insertion and expulsion that occurs during redox cycling. Significant volume changes occur through oxidation and reduction reactions at corresponding electrodes through exchanges of ions with an electrolyte.

The actuator is formed using a sandwich of two conducting polymer electrodes, usually polypyrrole or polyaniline dropped in HCl, with an electrode between them. Conductive polymer actuators require voltages in the range of 1 – 5 V. The variation of the voltage can
control the actuation speed. Relatively high mechanical energy densities of over 20 \( J/cm^3 \) are attained with these materials; however, they possess low efficiencies at levels of 1% [15], [14].

**Carbon Nanotubes**

Carbon nanotubes have diamond-like mechanical properties. The actuation mechanism is through an electrolyte medium, and the change in bond length via the injection of charges affects the ionic charge balance between the nanotube and the electrolyte. The more charges that are injected, the greater the dimension change.

The main obstacle for commercialisation of this EAP is its high cost and difficulty of production. This type of actuator can be constructed by laminating two strips of a carbon nanotube sheet using an intermediate adhesive layer. It is then immersed in an electrolyte solution and an electrical connection made from the two nanotubes strips. A 1 \( V \) charge is required to cause bending and the direction depends on the polarity of the field [15].

### 2.2.4 Discussion of Electroactive Polymers

At present, EAPs are being used to operate small devices, like the gripper on the Nanorover and a small toy swimming fish. They are being used to create devices for delicate operations with relatively small movements. To use EAPs in the same way that pneumatic muscles have been used in muscle suits the appropriate type of EAP will have to be selected and made large enough, or, several used in combination to create the force required. At present there is not one EAP that stands out as an actuator, which could be used to aid the movement of human limbs. Several teams of researchers are currently developing them. This development is taking place partly as a response to a challenge created by Yoseph Bar-Cohen, a leading figure in EAP research. In 1999 he posed an arm-wrestling challenge to promote the realisation of human-like robots. Although he knew that an EAP that could actively challenge a human arm was currently impossible, he wanted to encourage research that could someday “improve many aspects of our lives where some of the possibilities include effective implants and smart prosthetics, active clothing, realistic biologically inspired robots and the fabrication of products with unmatched capabilities and dexterity” [50]. It took a further six years for the challenge to be tested. On March 7th, 2005 the first EAP
human arm-wrestling match was undertaken in San Diego, California. Three teams competed and their opposition was a 17 year old female student. Figure 2.8 shows the human / EAP arm wrestling matches. The competitors were from: Environmental Robots Incorporated (ERI), Swiss Federal Laboratories for Materials Testing and Research (EMPA), and Virginia Tech. On this occasion none of the teams managed to beat their human opposition. The longest to hold against the student was the arm from ERI and it lasted for 26 seconds [4].

The following year another competition was held and the same three teams entered. That year the EAP arms were not directly competing with a human. Each competing EAP actuated arm pulled on a cable that had a force gauge on its other end and was supported by a wrestling fixture as shown in Figure 2.9. The EAP actuated arms were tested for speed and pulling force capability. To simulate a wrestling action a 0.5 kg weight was mounted on the cable and was to be lifted to the top of the fixture (as shown in Figure 2.9) and the time to reach the top was measured. Once the weight reached the top, the cable was stretched and the gauge measured the force. The same student as used in the previous competition recorded a baseline measurement on the same equipment, and again she beat the competition. Table 2.3 shows the results. It can be seen that the results of the height lifted, force and speed are all lower than the human arm. With the speed being most notably low. It took the Virginia Tech and ERI arms over 3 minutes to achieve their final lifted height. No EAP robotic arms were ready to compete in 2007 or 2008 [4].

The research undertaken by the teams competing in Bar-Cohens Grand Challenge shows that at present there is not an EAP able to compete with a human muscle. The Virginia Tech engineering, science and mechanics team used ionic polymer gel actuation [55]. This
Table 2.3: Results of the 2006 EAP / Human Arm Wrestling Match

<table>
<thead>
<tr>
<th>Competitor</th>
<th>Lifted Height (Inches)</th>
<th>Force (lbf)</th>
<th>Speed (in/sec)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panna Felson</td>
<td>9.78</td>
<td>21.8</td>
<td>&gt;9.78</td>
<td>Baseline</td>
</tr>
<tr>
<td>VT - Eng. Sci. &amp; Mech</td>
<td>8.78</td>
<td>0.2</td>
<td>0.037</td>
<td>Strongest</td>
</tr>
<tr>
<td>ERI</td>
<td>3.28</td>
<td>0.2</td>
<td>0.045</td>
<td>Fastest</td>
</tr>
<tr>
<td>VT - Mech. Eng.</td>
<td>Failure on Activation</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

has good contraction properties, with up to 40% contraction. This is reflected in the lifted height of the team’s arm. For use in this project, it is not a feasible choice as it has very slow contraction time and a gel would be difficult to work with. The Virginia Tech mechanical engineering team chose to use Dielectric EAPs [4] in their arm, which unfortunately failed on test day. These do have the potential to one day challenge human muscle as it is capable of producing 30 times as much force as human muscle gram for gram, but unfortunately it requires several thousand volts to achieve actuation which would not be safe to be incorporated into a garment to be worn near the body. The ERI team, which used IMPCs [4] in their arm, has the advantage that far lower voltages are required for actuation in comparison to the dielectric polymer, but it can be seen that it has slow activation, so again is not suitable yet for use in a garment for arm augmentation. Several of the EAPs can be disregarded for use in a wearable garment on a practical level, such as their response time or nature of the material. Liquid crystal elastomer materials would be discounted due to their slow response time, and nanotube materials due to their high cost and difficulty of production.

It can be seen that at present there is not a suitable EAP that has all the qualities required to be used in a wearable garment for arm augmentation. Further development in this field is still required to develop an EAP, which has:
• fast contraction and relaxation response;
• a practical physical form;
• requires low voltages for actuation;
• capable of holding the strain;
• operational under normal room conditions.

Although EAPs were not the right choice for this project, it can be assumed that with the continual advancement in technology, in the future an appropriate EAP will be developed which will be suitable for such a purpose. The next section will discuss the possibility of using pneumatic artificial muscles in this project.

2.3 Pneumatic Artificial Muscles

2.3.1 Introduction

A pneumatic artificial muscle (PAM) is basically a membrane which when inflated expands radially and contracts axially. This generates a pulling force along the longitudinal axis [71]. PAMs have been developed to address the compliance and control issues of conventional cylindrical actuators. The cylinder / piston is replaced by a flexible actuator which still provides good power to weight performance and several other positive properties [26]. As cited by Daerden [25], the first fluid driven muscle actuator was invented by the Russian inventor S. Garasiev in 1930. Since this time many muscle-like actuators have been developed, the types of which can be classified by their design. Braided, netted and embedded pneumatic actuators will be discussed in this section.

2.3.2 Braided Muscles

Pierce Expandable Cover

The earliest example of a braided artificial muscle was subject to a patent application in 1936. A second application from 1940 expanded on the idea. This was Pierce’s expandible
cover, as shown in Figure 2.10. The earlier patent related to just the braided shell and end fittings. The shell was braided using metal wires, which produced a cover with great strength. On expansion the metal wires would produce minimal friction. Pierce stated that one use of the expansible cover would be to replace the use of dynamite in coal mining. Rubber bladders would be inserted into the expansible covers and the “cartridges” inserted into holes in the mine wall. On inflation of the rubber bladder with oil (stated in the 1940 patent) the actuator would expand up to 2.5 times in diameter, cause the wall to crack and force the coal down [60]. It was not until the 1940 patent that the use of the internal rubber bladder was patented [61].

![Figure 2.10: Pierce Expansible Cover](image)

McKibben Muscle

The most studied and well known braided artificial muscle is the McKibben muscle. It was invented in the 1950s and was developed for use in artificial limbs [15]. It was named the McKibben muscle after its inventor, American physicist Joseph L. McKibben [49]. The McKibben style of artificial muscle has been popular and widely used for robotic and artificial limb applications because it possesses many of the properties of biological skeletal muscle. Its characteristics include being spring-like, flexible and low in weight [31]. They also have a high force to weight ratio, so they are effective for mobile robots [15].
2.3 Pneumatic Artificial Muscles

Structure

The McKibben muscle has a similar structure to the earlier Pierce Expansible Cover. The McKibben pneumatic muscles are composed of a gas impermeable rubber or elastic bladder, encased by a braided sleeve. As shown by Figure 2.11 the braid fibres run helically around the muscle’s longitudinal axis at an angle of $+\theta$ and $-\theta$ [25]. Unlike Pierce’s wire braided shell, the Mckibben braid fibres are produced using a flexible fibre, which is non-extensible, or has very high longitudinal stiffness [21]. Nylon is often used. The braided shell also protects the inner bladder from over inflating and rupturing. The inner bladder and the braided shell are attached to end caps, which form the termination connectors and seal the muscle. One air cap is sealed while the other acts as the air input channel [26].

![Figure 2.11: Exploded Diagram of McKibben Muscle Showing Bladder and Shell](21)

Contraction

When the inner bladder is inflated, it presses laterally against the braided sleeve. The internal pressure is balanced by the braided fibre tension due to the fibre curvature about the bladder [25]. Due to the non-extensibility of the fibres in the braided shell, the actuator shortens according to its volume increase and / or produces tension when coupled with a mechanical load [21]. The shell acts to keep the cylindrical form of the muscle. The force generated by a McKibben muscle is dependent on the weave of the braid, the properties of the bladder, actuation pressure and muscle length. McKibben muscles can be made in a variety of sizes [31]. The Shadow Robot Company produce McKibben muscles in three standard sizes of 7 mm, 20 mm and 30 mm diameter, which have a maximum pull of 7 Kg, 20 Kg and 70 Kg respectively [5]. Davis et al [26] state that muscle lengths can range from under 10 cm to up to 400 cm with diameters ranging from less than 10 mm to up to 70 mm. The typical operating gauge pressure range of McKibben Muscles is 1 – 5 bar. The maximum allowable gauge pressure is determined by the strength of the bladder; too high
a pressure would make the bladder bulge through the mesh of the braid and it would subsequently burst. The higher this pressure the more energy can be transferred, but equally the higher the pressure the thicker the bladder needs to be. So in order to accommodate the high pressures required to lift heavy loads, a tough bladder is used. As a result of this, low forces cannot be generated, as low pressures are unable to expand the tough bladder [25].

Figure 2.12: McKibben Muscle Tension (N) and Hysteresis at Isobaric Conditions (0, 1, 2, 3, 4 and 5 bar) [21]

Figure 2.12 shows the displacement of a McKibben muscle at increasing pressures. Arrows show the path of the muscle contracting and relaxing. It can be seen that displacement decreases as the load increases. The graph shows a considerable amount of hysteresis. It is widely acknowledged that this hysteresis is due to the dry friction between the bladder and the braided shell.

Disadvantages

McKibben muscles are widely used in the robotic field, but there are several drawbacks to this type of actuator.

1. Due to dry friction between the braid and the bladder these actuators have high levels of hysteresis, as described by Chou and Hannaford (1996) [21]. This has an adverse effect on actuator behaviour, requiring the use of complex actuator models and control,
2.3 Pneumatic Artificial Muscles

e.g. Tondu (1997) and Caldwell et al. (1995) [69], [18].

2. Deformation of the rubber bladder lowers the generated force because of the energy it requires. This effect depends on the toughness of the rubber used; the tougher the rubber the stronger the effect [24].

3. The applied pressure has to exceed a threshold value to start the expansion of the tube. Again, this value depends on the toughness of the rubber [24].

4. Membrane failure. Klute and Hannaford (1998) [37] describe rubber fatigue failure as the most common failure mode. Many users also complain of wires snapping at the end point of the actuator, i.e. where the bladder and shell are clamped together [24].

2.3.3 Netted Muscles

Netted muscles vary from braided muscles by the density of the material surrounding the inner tube. The net has a much looser construction with relatively large holes, whilst a braid is a tight woven structure. This type of pneumatic muscle will only withstand low pressures due to the open structure of the outer shell. High pressures would cause the bladder to bulge through the netting, possibly causing permanent deformation of the bladder.

Yarlott Pneumatic Net Muscle

This 1972 US patent [76] describes a “fluid actuator” which comprises of an elastomeric material bladder in a prolate spheroid shape. The bladder is netted by a series of rigid strands running axially from end to end embedded in the elastomeric bladder. A strand wound round and embedded into the bladder to form the mesh shell radially reinforces the bladder. On inflation a spheroid shape is produced. On deflation, the axially positioned strands straighten to force air out of the structure. As seen in the end-on view in Figure 2.13, the rigid strands straighten with the bladder protruding out between the strands to form a fluted configuration. On inflation the bladder bulges out of the mesh structure. Due to the contraction of this type of actuator it was designed to function at low pressures. Daerden [25] states values as low as 0.017 bar.
Kukolj Netted Pneumatic Muscle

This muscle patented in 1988 by M. Kukolj [46] is a variation on the McKibben muscle. An elastomeric sleeve is used for the bladder and unlike the McKibben muscle, which uses a tight braid for the outer shell; the Kukolj muscle uses a non-extensible open meshed net.

When the muscle is un-inflated the net fits loosely about the bladder in a bag-like manner. The slack only disappears at a certain level of inflation. The mesh network has a higher density at the ends of the structures compared to the middle. The more open structure in the central section allows the muscle to expand more in this area to produce a spindle shape on inflation. This spindle shape mimics the shape of a biological skeletal muscle. Figure 2.14 shows the Kukolj Muscle in its un-inflated, non-loaded condition, and in a set-up, lifting a weight mounted hanging from a hinged arm, showing the actuator in relaxation and contraction conditions.

Immega and Kukolj Pneumatic Net Muscle

This artificial muscle actuator patented in 1990 by G. Immega and M. Kukolj [33] consists of a convex polyhedral bladder harnessed by a network of linked cables to form a type of netting. A fluid impermeable and substantially non-elastic flexible material is used for the bladder. The network of non-extensible cables extends over the base seams of the protrusions. The inventors claim “the percentage contraction is large due to the ability of the
enclosures to articulate without excessive radial bulging". Contractions of over 45% were produced from certain designs. Figures 2.15 and 2.16 shows the variation in designs, which show different numbers of faces and shapes of protrusions.
Figure 2.16: Immega and Kukolj Axially Contractable Actuator, Design Variations
2.3.4 Embedded Muscles

Embedded muscles have the load bearing structures embedded in the muscle membrane a selection of which will be described in the following section.

**Baldwin Muscle**

The Baldwin muscle, as shown in Figure 2.17, consists of a very thin surgical rubber membrane with glass fibre axial filaments embedded into it. This results in the membrane having a modulus of elasticity in the axial direction that is much higher than that in the direction perpendicular to the fibres. This muscle structure shows a very low level of hysteresis. This is due to the very thin membrane and absence of friction as it is a single layered structure. Due to the high radial expansion produced with this structure, air pressure has to be limited to low values of between $0.1 - 1 \text{ bar}$. Forces of up to 1600 $N$ have been recorded at these low pressures [13].

![Baldwin Embedded Actuator](image1)

**Paynter Knitted Muscle**

This design, patented in 1988 by Paynter [57] uses a spherical shaped bladder as shown in Figure 2.18, which is reinforced by a knitted sleeve bonded to its surface. The bladder used is a flexible elastomeric material. A tubular sleeve is knitted to encase the bladder, which has a more loosely knitted central region to mirror the same spherical shape of the bladder,

![Paynter Knitted Muscle](image2)
so to define an outer limit to radial expansion of the bladder and reinforce the bladder on inflation at high pressure. The bladder and the knitted sleeve are bonded together and cured to form an integrally bonded structure. This muscle operates at 2 bar and its life expectancy was noted to be “many hundreds of thousands of cycles”.

Figure 2.18: Paynter Knitted Muscle

Paynter Hyperboloid Muscle

This alternative design shown in Figure 2.19, also patented by Paynter in 1988 [56] shows a muscle, which is contained by a series of tension element strands. When the muscle is in its relaxed state, these strands that are bonded to the bladder take the shape of a hyperboloid of revolution. These inextensible but flexible tension element strands, possibly Kevlar or a metal wire, run between end fittings. They serve to constrain the resilient, flexible and stretchable, elastomeric bladder of the actuator on inflation to create a near spherical container, as shown in Figure 2.19. A maximum contraction of about 25% and tensions of 500N at 2 bar at zero contraction are mentioned for a muscle 2.5 cm long and of 1.25 cm end fitting diameter.

Pleated Pneumatic Muscle

The pleated pneumatic artificial muscle (PPAM) is an artificial muscle developed by a team at Vrije Universiteit, Brussels to overcome several recognised weak points of the traditional McKibben braided muscle, as discussed in Section 2.3.2. From these factors it was decided
to produce the muscle from only one layer of material and deformation should be avoided. The muscle was designed used “membrane rearranging” to allow for inflation. This means that instead of the material stretching on inflation, the surface area of the material stays constant, but unwraps on inflation. The muscle uses a cylindrical membrane with high tensile stiffness and high flexibility, which is folded along the central axis. The membrane is locked into fittings at both ends that also carry the gas inlet and outlet ducts. When the muscle is inflated, the membrane unfolds and the muscle shortens and bulges, free of radial stress. As the membrane has a high tensile stiffness, the expansion is highest in the middle of the membrane and gradually reduces toward the ends where no expansion can occur. As the membrane is folded and a single layer, no friction is involved in the process of inflation. As a result of this, no friction-related hysteresis would occur. As the unfolding process requires nominal levels of energy, there is no loss of output force [24]. Figure 2.20 shows the contraction process of a PPAM.

Other properties claimed for this type of pneumatic muscle include:

- high torque / weight and power / weight ratios;
- muscle has natural compliance;
- the actuator can be positioned at the joint without complex gearing mechanisms;
- adaptable passive behaviour suited for energy storage;
- shock absorbance during impact.

This actuator is also relatively lightweight. The weights of the parts are 7.3 g for the membrane, 12.5 g for the plug, 1.8 g for the resin filling and 11.2 g for the outer ring. The
total muscle weight, using two basic plugs is 58.3 g [72].

Saga Embedded Muscle

A recent development in the field of pneumatic artificial muscles has been the development by N. Saga, et al of an artificial muscle actuator that is reinforced with straight carbon fibres. This actuator was developed to overcome the large heat and mechanical loss due to friction created in the traditional McKibben type muscle. As previously discussed, friction was produced due to the expansion and contraction of the braided sleeve rubbing on the inner rubber bladder. The muscle that the team produced used high intensity Carbon fibres (previously Kevlar [65]) arranged axially in a silicone tube so eliminating the friction caused by requiring an outer shell. Unlike the McKibben type muscle that is radially restrained by the braided outer shell, this muscle is only restrained by the elastic force of the silicone rubber [66]. It does not require a sleeve, which results in a long life span. It can also express an aeolotropic property due to the way the fibres are knitted into the tube [53].
2.3 Pneumatic Artificial Muscles

Structure

The pneumatic artificial muscle actuator developed, as shown in Figure 2.21, is made from a tube of silicon rubber and multiple carbon paper fibres inserted axially to strengthen the axis [67]. The carbon fibre is composed of thin fibres bunched together. As a result, when the artificial muscle expands, the expansion of the rubber tube can be controlled because the bunches of fibres splay out with the expanding rubber. Due to this, the rubber tube could be thinned. The developed artificial muscle has a length of 100 $mm$, an outer diameter of 12 $mm$ and an inner diameter of 9 $mm$. Further specification can be seen in Table 2.4. The team hoped that because the silicone rubber they used had a low degree of elasticity, the pressures required to produce a high level of contraction would be low [66].

![Image of Inflation and Deflation of Artificial Muscle also Showing Cross Sectional View](image)

| Inner diameter $mm$ | $\phi$ 9 |
| Outer diameter $mm$ | $\phi$ 12 |
| Length of artificial muscle $mm$ | 100 |
| Mass of artificial muscle | 45g |
| Silicon rubber | SE1120U (Toray Dow-Corning Silicone Co.) |
| Reinforced fibres | Carbon – fibre |
| Youngs modulus of fibres | 49 – 1000 $GPa$ |
| Tensile strength of fibres | 1100 – 6000 $MPa$ |
| Number of fibre band | 10 |

Table 2.4: Specification of Muscle Structure [67]
The procedure for fabricating the artificial muscle was as follows.

1. The glass tube in the moving tray is soaked in pre-vulcanised liquid latex.

2. The glass tube is removed from the rubber liquid after one minute. Here, the liquid rubber evenly adheres to the glass tube by removing the glass tube at a constant speed.

3. The rubber adhering to the glass tube is vulcanised in a constant temperature furnace. At this time, the motor rotates the glass tube so that the rubber film may have a uniform thickness.

4. A basic tube is finished to the desired thickness, by repeating Step 1 to Step 3 several times. Here, the film thickness of the rubber, which adheres to the glass tube, increases in 0.1 mm increments with each repetition of Step 1 to Step 3.

5. The strings to restrain the rubber are placed on the glass tube.

6. The strings for restraint are fixed to the basic tube, again by repeating Step 1 to Step 3.

7. The rubber tube is separated from the glass tube by applying powder [53].

**Contraction of the Muscle**

Figure 2.22 shows the experimental setup used to measure the characteristics of the artificial muscle. The experimental setup consists of the artificial muscle attached to a load via a pulley arrangement. The end of the artificial muscle will move to the left or right depending on the expansion or contraction of the actuator, and a laser position sensor monitors movement. The internal pressure and load parameters can be changed to see how they affect the contraction and response characteristics.

Initial testing of the muscle determined the relationship between the initial length of the uninflated muscle and the contraction levels at different pressures. This can be seen by Figure 2.23. The test was implemented by extending the initial length of the artificial muscle by 5 mm and by changing inside pressure from 0.1 MPa up to 0.2 MPa with 0.02 MPa increments, and measuring the amount of contraction. With an initial length of less than 50 mm and inside pressure of 0.1 MPa the contraction ratio was low at 4%, and with
an initial length of more than 80 mm and inside pressure of 0.2 MPa the contraction ratio decreases. This verifies that if the initial length of the artificial muscle is short with low inside pressure, the contraction ratio is low, and as the initial length increases with high pressure, the contraction ratio decreases [67].

Originally the design of this muscle was similar in appearance to the traditional McKibben type muscle; it was a silicone cylinder, which on inflation expanded to become a fatter, shorter cylinder. After further development, this design was altered to incorporate an aluminium ring around the centre of the silicone tube. Figure 2.24 shows the relation between pressure and the contraction of the artificial muscle. The initial length of the artificial muscle was 100 mm. With no ring, the maximum contraction was 17 mm and with one ring it was 23 mm, a 1.4 times improvement. Figure 2.24 also shows the result of adding two rings placed equal distance along the length of the silicone tube. It shows that the amount of contraction decreases when compared to one ring. The maximum contraction when two rings are used was 21%. Although this was higher than the 17% contraction when no rings were used, it can be seen that when one ring was used the contraction was greatest at 23%. This confirmed that mounting one ring increased the contractive capability.
Figure 2.23: Contraction at Various Pressures

Figure 2.24: Measured Values of Contraction–Pressure at Various Pressures Using 0, 1, or 2 Rings

[67]
2.3.5 Discussion of Pneumatic Artificial Muscles

This section on PAMs has discussed 70 years of design and development in pneumatic artificial muscles. The most recent development had occurred in the braided and embedded areas. The netted structure designs have been limited in development and popularity, possibly due to the open structure of the shell, which only allows for low pressures to be used. This in turn will reduce the potential load capacity. Apart from the popular and widely used McKibben muscle, PAMs with the most literature on them are the pleated pneumatic muscle from Virje Universiteit and the Saga embedded muscle. These are both embedded style muscles and are both used in robotic applications. The pleated pneumatic muscle has been incorporated into a biped robot called “Lucy”. Lucy can be seen in Figure 2.25. As stated by Verrelst 2005, Lucy weighs less than 30 Kg, is 1.5 m tall and the body is cast out of an aluminium alloy. Lucy is a biped and both legs are identical. Each leg uses six muscles arranged antagonistically to produce movement. Saga’s embedded muscles have been incorporated into a robotic arm, Figure 2.26. This arm uses eight PAMs also antagonistically arranged in each section of the arm. The upper and lower sections of the arm are connected by wires and a pulley which act as an elbow and produce movement in the lower arm when certain muscles are under inflation. It has a length of 0.683 m and a width of 0.175 m and with a total weight of 3.3 Kg, it is comparable in weight to an actual arm [67]; by weighing arms from cadavers, Clauser (1969) states that the average human arm weighs 3.126 Kg [23], and Chandler (1975) states it as 3.35 Kg [19]. The arm has an operating angle of 0 to 118°, which is just 27° lower than the typical human arm.

Both teams successfully created robots using pneumatic artificial muscles, rather than using motors, which is the more traditional actuation mechanism for robots. Both of these applications of PAMs have been concerned with the movement produced with the muscles and no data are provided for any load they can lift, which would be most relevant with the robotic arm. Neither of these systems was designed as an orthotic or prosthetic device so it is hard to compare them to the work of this project, but they are impressive examples of PAMs helping to mimic human limb function.

It can be seen that the PAM is currently capable of a high amount of contraction with a fast response time. Due to these reasons, they are currently the better choice than EAPs for
using in this project and incorporating into a wearable orthotic device or “muscle suit”. For this reason, EAPs will no longer be considered for further use and PAMs will be the artificial muscle taken forward. The following chapter discusses the different types of actuated orthotics, past and present. By analysing the current status of these muscle suits, along with PAMs, the best way to incorporate a pneumatic actuator into a textile garment is considered.

Figure 2.25: Biped Lucy Developed by Virje Universiteit, Brussels [72]
2.3 Pneumatic Artificial Muscles

Figure 2.26: Saga Robotic Arm

(a) Initial state

(b) Drive state

[67]
Chapter 3

Current Status of Muscle Suits

3.1 Introduction

This project is looking for artificial muscles that can be used to aid the movement of the upper body. For this reason muscle suits and orthoses aiding movement of the upper body, mainly the arms and hands, have been investigated. There are several muscle suits, which have been developed to be worn by the carer to assist in lifting and carrying of a patient. These include TEM-LXI, the walking support apparatus by Hitachi Ltd, HARO and the Power Assist Suit. These exoskeleton type muscle suits are discussed in this chapter, but not in great detail, as they are not designed to aid everyday living. This background research has focused on the muscle assisting devices that can be worn comfortably to aid with daily life.

3.2 Orthotic Muscle Suits

This section discusses four different types of wearable muscle suits. They each show various methods of actuation for moving the arms, hands and fingers. They are categorised separately from devices, which augment the movement of the whole body. These orthotic devices are designed specifically for certain areas and were originally developed to assist the elderly or those with muscular deficiencies.
3.2.1 Artificial Muscle Driven Flexor Hinge Splint

This system is the earliest known use of a pneumatic type muscle being used to aid movement in an orthotic device. Specifically, a McKibben muscle was used. This device was developed in the 1960s and discussed in a 1963 issue of The Journal of Bone and Joint Surgery (V. Nickel et al). The device was developed for persons with severely paralysed hands to help them create a three fingered pinch. Figure 3.1 shows the device, as it would have looked on the patients arm. After surgery to pin the thumb, index and middle fingers into the correct positions a brace is used on the arm and hand. The thumb, index and middle fingers are held in position by metal bracings and there is a flexor hinge in line with the knuckles. To close the fingers and create a three fingered pinch, the pneumatic actuator is inflated by means of a carbon dioxide canister, which the wearer controls via a push valve. As the artificial muscle inflates, its length shortens and pulls on the flexor hinge, which causes the index and middle fingers to close in towards the thumb. Opening of the fingers occurs when the pneumatic actuator is deflated. This is accompanied by a spring, which opens the fingers [54].

Figure 3.1: Flexor Driven Hinge Splint with Pneumatic Muscle Actuator [54]
3.2.2 The SMART Wrist-Hand Orthosis

John B. Makaran et al reports in 1993 of shape memory alloys (SMAs) being used to create a wrist-hand orthosis. This flexor-hinge hand orthosis is based on a modified three-jaw chuck. This device allows the fingers to move inwards towards the wrist, and the thumb to move inwards towards the palm. The orthosis can be seen in Figure 3.2. This device uses SMAs, but other similar actuators can be used such as McKibben muscles, carbon dioxide or an electric motor. The SMA is the actuating element to convert electric energy into mechanical work. The shape memory effect (SME) allows the SMA to deform at low temperatures and recover to its original shape under heating. This effect is due to the phase transformation in the metal from a low temperature disorganised crystal structure to a reorganised crystal structure at a high temperature. The SMA used for this device was a nickel titanium alloy called “Nitinol”. It is resistant to corrosion and has high electrical resistance [51].

If the user wishes to grasp an object, they activate the SMA strand to close the hand. To minimise power consumption, the position of the hand is maintained using a rotary ratchet mounted by the knuckles. When the user wants to close their hand, the SMA shortens causing the ratchet to rotate. This is attached to the orthosis, which the fingers are strapped into, so causing the hand to close. To open, there is another SMA, which is attached to the pawl. When the SMA is activated, it shortens, the pawl releases the spring loaded ratchet and the tension in the spring is released and the hand opens [51].
The SMA used has a high electrical resistance, so an electric current can be used to induce SME. A “sip and puff” mechanism can be used to allow the user to control how much electric current passes through the SMA or when to open or close their hand, by using an inhalation or exhalation of their breath. An exhalation activates one switch closure and an inhalation activates a second switch closure [51]. Myoelectric signals from intact muscles picked up by electrodes and then amplified could be used to control the passage of current to the SMA. For example a biceps flex could activate the device.

The advantages of this system include the orthosis being lightweight and durable. The SMA used has a high fatigue life of $10^7$ cycles and the wires used cost less than 15 Canadian dollars at the time of the article being published, so the orthosis is cheap to produce. The creators have suggested improvements to the design, which include using thinner SMA wires to improve the response time. The response time at present is still relatively fast at 2 seconds to close the hand. The orthosis uses an aluminium frame, so using plastic instead would decrease the weight and increase the comfort and eliminate the possibility of electrical shorts [51]. To make the orthosis look more glove-like would make it more aesthetically pleasing.

This device uses a simple and reliable mechanical system. It is only possible to make a gripping motion whilst wearing the device, as the individual fingers cannot be moved independently. The suggestion of using myoelectric signals to activate the opening and closing of the hand is very interesting. This method of operation along with the use of shape memory alloys could be used in other areas of the body. At present this device uses a frame to pull the fingers into closing. A possible improvement would be to see if the device could work without the frame and use a pull on a textile garment to create a more glove-like appearance.

### 3.2.3 Kobayashi Muscle Suit

In 2002 Hiroshi Kobayashi created a wearable robot for human power support. It was developed to help Japan’s aging society retain their independence and to provide muscular support for the paralysed, those unable to move unaided, or for use in rehabilitation. A muscle suit was developed which is a skeleton robot or muscular support apparatus, which allows the wearer to move by just wearing it. Unlike conventional robots it does not rotate
Chapter 3: Current Status of Muscle Suits

the joints directly, but moves the body with actuators acting like human muscles. Kobayashi defined 7 considerations that the suit must conform to. They are:

- must not restrict users;
- inexpensive;
- support mental health;
- lightweight and reasonably sized for use in daily life;
- reduce physical burden on helper;
- inner skeleton must be lightweight;
- use actuators.

The basic idea is that a pneumatic actuator is sewn onto a garment and when pressurised air is applied, the actuator contracts and the garment will pull on the limb, thus creating movement. Kobayashi wanted his suit to have the following qualities:

- enable the wearer to realise any kind of motion;
- uses the McKibben muscle, which is lightweight and has a large force output;
- provide lightweight assistance sufficient for muscular support without needing a metal frame;
- enable independent movement by the wearer.

Another advantage of using McKibben muscles is that they are soft and flexible. Because of this they can be arranged so they conform to the curved surface of the wearer’s body, as shown in Figure 3.3.

A life-sized doll was used to test the movement of the prototype suit. The suit had six degrees of freedom – three for the shoulder (forwards and backwards, left and right and horizontal), one at the upper arm for torsion, one at the elbow for bending and one at the wrist to move the palm to the left and right. This experiment was used to determine the length
and placement of the muscles. It also showed that a human could wear the suit for implementation of motion. The limitations of the suit were also seen. Abduction (lifting of the arm) could only reach 40 degrees due to weight requirements and range of motion [39] [41].

By 2004 a frame had been incorporated into the suit to overcome the problems found during the prototype testing, as shown in Figure 3.4. The frame, which is made from Chloroethene, uses mechanical joints. This frame has been used to help realise all the movements of the arms. The movements had not all been realised previously as the suit was using the wearer’s body as a frame. This meant that the distance from the end of the actuator to the joint was quite long. In the human body it is short as the muscles are connected directly to the bones via tendons. This gives humans and other mammals a wide range of movement, as the distance from the joint to the end of a muscle is relatively short. With the frame, it is easier to realise all motions of the arms with the muscle suit, as it is the distance from the mechanical joint to the actuator which is important, not the distance to the wearer’s joint. The frame also reduces loss of motion caused by slippage and slack. The Chloroethene frame is stiff and so overcomes the issue of slippage and the displacement of the actuator can be conveyed directly to the muscle suit. It does not require a tight fit which would be uncomfortable and difficult to get in and out of. Another worry with the muscle suit is that it may apply a large load onto the wearer’s joints and bones, but with the frame, the wearer is moved by contracting the surface of the frame. The suit does not use the wearer’s bones and joints as a brace so no heavy stresses or loads are imposed on them. The total weight of the suit is 3 $Kg$. If the frame was to be made of fibre reinforced plastic, the weight, it was claimed, could be reduced to 2 $Kg$ [41].
This muscle suit started off as a wearable garment with McKibben muscle sewn into it. The suit has developed into a large bulky garment, which can be seen in Figure 3.4. This has been due to the problems of lack and loss of movement in the garment suit requiring the use of a frame. The frame consists of 12 parts. Hollow cylinders are used to encase the wearer’s arms with a mechanical joint at the elbow and shoulder. These are attached to an over the head shoulder piece [41]. Although this does allow the wearer to realise seven upper limb motions, it looks bulky and possibly uncomfortable. Kobayashi has suggested that without a frame, human bones and joints may be under heavy loads and stresses, but
with the frame it looks difficult to wear especially in daily life, so a compromise may need to be made. If such a device was to be used in manual labour, obviously stresses and loads on the workers bones and joints would be undesirable, but for someone who would use it in daily life, comfort and ease of use may be more important.

3.2.4 Wearable Power Assist Device

D. Sasaki et al at Okayama University, Japan developed the Wearable Power Assist device for hand grasping in 2004. This uses pneumatic muscles, but not the McKibben type. The device uses a curved rubber muscle on the back of the fingers and thumb and a linear rubber muscle at the base of the thumb. The figuration of these muscles on the device is illustrated by Figure 3.6.

![Figure 3.6: Arrangement of Pneumatic Muscles on the Hand Orthosis](Image)

The curved rubber muscle, Figure 3.7, consists of a rubber inner tube with a polyester shell. It is reinforced along one side with a fibre tape. This reinforcement causes the muscle to curl around the tape when inflated. The maximum force generated from this muscle is about 23 N at 5 bar.

The linear rubber muscle, Figure 3.8, again consists of a rubber tube and polyester shell. As it is not reinforced with the fibre tape, it extends in the axial direction. In like-for-like comparison with the McKibben muscle, the maximum contraction force of the linear muscle
Figure 3.7: Curved Rubber Muscle showing Initial Image and Pressurised State

is about 5 times lower than the McKibben muscle, but the linear muscle’s percentage contraction is more than double.

Figure 3.8: Linear Rubber Muscle showing Initial and Pressurised State

When the curved muscles are inflated, they force the fingers and thumb to curl inwards towards the palm, allowing the user to grip. The linear muscle moves the thumb in towards the middle of the palm. Using these motions, six of the main hand movements can be realised.

This device is controlled by an expiration switch, which is similar in function to the “sip and puff” mechanism used in the SMART wrist-hand orthosis. This means that the wearer is again able to control the movement of the device using their own breath. The switch consists of a silicone tube connected with an air pressure sensor. The wearer breathes into the tube and when pressure from expiration becomes higher than the pressure threshold, the device is switched on or off.

To test the effectiveness of this device Mosso’s ergograph was used to measure muscular fatigue with and without wearing the device. A finger was attached to a weight via a wire and the finger bent and straightened continuously. The displacement of the weight was measured by a potentiometer. The results showed that the change of amplitude with the
device is smaller than without it, showing it is effective in decreasing muscular fatigue [68].

Compared to the hand orthosis powered by SMAs, this device is smaller and less bulky. It is designed around a glove so it looks more pleasing. Again the wearer is able to control the movement of their hand, this time with an expiration switch. The design and usage of the pneumatic muscles is very innovative. It is unclear if they could be scaled up to work on other parts of the body and if their mechanism would be useful, as biological muscles do not curl or extend in that fashion. This device does not use a frame to protect the bones of the wearer, but as the movements are smaller and the overall load put on them is lower, it may not be required.

3.3 Exoskeleton Muscle Suits

A short discussion of human exoskeletons currently under development is included. Although these exoskeletons mainly do not use pneumatic artificial muscles, or are lightweight or easy to wear, they are important to consider, as they are being developed to aid human force augmentation, in areas relevant to this project. These suits have been designed for use by the military, for heavy lifting and fatigue reduction, for use by care-givers, the emergency services and the construction industries [17].

3.3.1 Hardiman 1

An early motorised exoskeleton dates back to 1965 where General Electric Research and Development Centre in USA developed a self standing electric exoskeleton powered by hydraulics. Shown in Figure 3.9, “Hardiman 1” as it was called was as heavy as a car but could allow the human wearing the robot to lift vast weights with ease. Unfortunately this robot was not fully functional and the inventors could only get one of the arms to work. An account from a company report describes how when both legs were operated at once it would lead to “violent and uncontrollable motion” [74].

3.3.2 DARPA

In 2000, the US military’s research organisation DARPA began funding a program to develop full body force amplification exoskeletons for its soldiers by 2005. Their aim was to
create a suit, which would increase both the lethality and survivability of their troops. Soldiers would be able to carry larger weapons, more equipment and have greater strength and endurance. Figure 3.10 shows the image that DARPA were aiming for [17].

3.3.3 Berkeley’s Lower Extremity Exoskeleton (BLEEX)

A team at Berkeley Robotics Laboratory, University of California, created a device for the legs, which allows the wearer to carry heavy loads whilst only feeling like they are carrying a few kilos. The first prototype experimental exoskeleton comprised of two hydraulically powered anthropomorphic legs, a power unit, and a backpack-like frame on which a variety of loads can be mounted. This can be seen in Figure 3.11. The exoskeleton allows a person to comfortably squat, bend, swing from side to side, twist, walk and run on ascending and descending slopes, and step over and under obstructions while carrying equipment and supplies. While wearing the exoskeleton, the wearer can carry significant loads over considerable distances without reducing agility, thus significantly increasing physical effectiveness [64].
3.3 Exoskeleton Muscle Suits

3.3.4 Oak Ridge Exoskeleton

Researchers at Oak Ridge National Laboratory have developed a lifting machine, which is able to amplify hand motions with considerable strength, but with very high precision. This
has been developed to aid with the loading of machinery and weapons onto aircraft. It is able to lift 2,200 $Kg$ as if it were 4 $Kg$ [74]. This system was expected to weigh about 40 $Kg$ and be able to carry about 150 $Kg$ making the wearer about three times as strong [17].

3.3.5 **Active Support Splint (ASSIST)**

The Active Support Splint (ASSIST) developed by Keijiro Yamamoto of the Kanagawa Institute of Technology near Tokyo is an exoskeleton design to assist care-givers. It gives care-givers the extra strength they need to lift patients while avoiding back injuries. The suit, shown in Figure 3.12, uses computer-controlled, air-driven limbs that multiply the wearer’s strength dramatically. Sensors line the suit’s arms, back, and legs and relay muscle activity data to a small computer. This backpack-mounted computer instantly regulates how much air should flow in or out of high-pressure air actuators that are connected to an onboard air pump. As they inflate and deflate, the actuators add force to the wearer’s efforts and help manoeuvre the 45 lb suit. Yamamoto also found that a user wearing the suit could lift weight using half or less muscle power, i.e., muscle power doubled [47] [34].
3.3.6 Honda Walking Assist Device

Honda has developed the Walking Assist Device to help reduce injuries and fatigue of workers on its vehicle assembly lines, as shown in Figure 3.13. It is hoped that it could also help increase the independence of the elderly by replacing canes and walking frames. The device consists of a bicycle type seat with two jointed legs attached, which are connected to a pair of shoes. The user puts on the shoes and the seat fits between the legs. The walking assist device helps the user walk, crouch and stand without an excessive amount stress on the hips, knees and ankles. It runs on two motors connected to a lithium-ion battery and weighs less than 15 lb [8].
3.4 Discussion

The four featured types of orthotic muscle suit are all very different. They all have different actuation mechanisms, which are suited to the movement they create. It is unlikely that SMAs could be used as an actuator for areas of the body other than the hands as the actuation forces able to be generated are too low. It is possible that the curved and linear pneumatic muscles if increased in size adequately could have the power to be used in any other areas of the body. A possible place for this could be to move another joint like the elbow. Increasing the size of the pneumatic muscles may cause issues with joint strain. It could require the use of a frame to protect the bones. The upper body muscle suit could be improved upon, as at present the user does not operate it. An expiration switch or sip and puff mechanism could be used as with the other muscle suits studied. Another control mechanism could be to use myoelectricity. This is the technology of taking electrical signals from the muscles and converting them into an electrical current. If this current is amplified enough it could be able to trigger a motorised component in the muscle suit to perhaps turn on or off an air valve to contract or relax a McKibben muscle.

The exoskeleton muscle suits covered in this section all show different solutions to answer the same problem i.e. how to improve muscle strength and reduce muscle fatigue. They answer this problem using motors and hydraulics. The field of exoskeletons has come some distance since the Hardiman 1, which was unsafe. Products like the BLEEX exoskeleton
and the Oak Ridge exoskeleton show an improvement in exoskeleton design but are still a long way off DARPA’s aim of full body force amplification exoskeletons for its military. This was aimed to be ready by 2005. No information is available to announce if this adventurous plan has been fulfilled. As Figure 3.11 shows, to make the exoskeleton free from external power sources, a large power pack must be worn. Although in this image, not all of the backpack is taken up with the power unit, it is still adding extra weight and bulk which is a disadvantage to the wearer as apart from the extra weight, it may be impairing movement. A possible area for development is to produce a small lightweight and long lasting power pack. Any military with the technology able to improve strength and reduce muscle fatigue over extended periods with a small power unit would clearly be in an advantageous position.

The most recent exoskeleton development is that of the Honda Walking Assist Device. This device differs from the other devices as it is considerably smaller and is currently in regular use on the Honda production line. Honda has managed to overcome the problem of finding a lightweight power source and have therefore been able to produce a relatively lightweight exoskeleton.

The two sections of this chapter discussed muscle suits and exoskeletons. The main difference between these two research areas is that muscle suits have been produced to aid the movement of people who have a muscle weakness or deficiency, and exoskeletons have been produced for fully functioning people but to improve strength and reduce muscle fatigue. An area that has been unexplored is the combination of the two i.e. a muscle suit which can help augment movement for the muscular deficient, but also improve strength for fully functional wearers. The pneumatic muscle suits discussed in this chapter currently all use a McKibben or McKibben type actuator. There is a need to develop a soft and flexible actuator and textile materials have the potential to achieve this, thus differing from the traditional design. The textile actuator will then be incorporated into a wearable garment. The following chapter records the development of a new PAM with several developmental stages.
Chapter 4

Muscle Construction Development

4.1 Introduction

This chapter documents the initial design and development of a pneumatic artificial actuator. Section 2.3 discussed other types of PAMs and Chapter 3 discussed how some of these were incorporated into wearable muscle suits. The PAM developed in this project differs from these previously discussed designs as it was made primarily from textile materials. This produced a soft and flexible PAM, which although not suitable for industrial applications, it could be ideally suited for incorporation into a garment as it is lightweight and flexible.

To create a 3-Dimensional structure for the PAM, a number of panels were sewn together, similar in design to a beach ball. Variations in the size, shape and number of panels allowed for several 3-Dimensional muscle structures to be produced. Lengths of Kevlar were incorporated into the seams, which stiffened the structure and thus aid in maximizing muscle construction as discussed later in this chapter. This chapter discusses the design developments of the muscle shape and the methods used to produce an air-tight structure. This involved finding a suitable way to seal the seams.
4.2 Initial Design

To find the best shape and design for an artificial muscle, which would have a good amount of contraction, a number of prototypes were created. These prototypes are pictured in Figure 4.1. For these sample muscles, an unbleached woven cotton fabric was used. The muscles that were created were made up of oval segments of the fabric with the seams overlocked together. This overlocking stitch was approximately 5 mm in width. The segments were cut so the warp direction was used for the longest length of each segment. As the fabric used was not gas impermeable, a bladder was used to contain the air. The bladder used was a small plastic bag, the end of which was sewn into one end of the muscle. When the bag was filled with air, it expanded to the shape of the surrounding fabric shell. Although it is unlikely that the bag could fill the complete volume of the shell, it gave a good indication of the final shape and size of the inflated muscle and gave a rough idea of how much it would contract.

To determine a possible shape for the muscle structure, nine different designs were made up. The amount of contraction was measured and the overall shape was studied to determine the practicality of the design. The contraction at this stage was simply measured by placing the un-inflated and then inflated muscle structure against a ruler to measure the length of the vertical axis. The details of the designs were as follows in Table 4.1. Samples 7 - 9 used two different sized segments, so both are indicated. Samples 8 and 9 used double layered segments.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Shape of Structure</th>
<th>Number of Segments</th>
<th>Segment Width mm</th>
<th>Segment Height mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Round</td>
<td>5</td>
<td>180</td>
<td>75</td>
</tr>
<tr>
<td>2</td>
<td>Oval</td>
<td>6</td>
<td>200</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>Oval</td>
<td>8</td>
<td>200</td>
<td>35</td>
</tr>
<tr>
<td>4</td>
<td>Spindle</td>
<td>5</td>
<td>170</td>
<td>65</td>
</tr>
<tr>
<td>5</td>
<td>Spindle</td>
<td>5</td>
<td>200</td>
<td>75</td>
</tr>
<tr>
<td>6</td>
<td>Spindle</td>
<td>6</td>
<td>220</td>
<td>65</td>
</tr>
<tr>
<td>7</td>
<td>Flat Oval</td>
<td>6</td>
<td>230</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>230</td>
<td>75</td>
</tr>
<tr>
<td>8</td>
<td>Flat Oval</td>
<td>6</td>
<td>230</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2x2</td>
<td>230</td>
<td>75</td>
</tr>
<tr>
<td>9</td>
<td>Flat Oval</td>
<td>9</td>
<td>230</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1x2</td>
<td>230</td>
<td>105</td>
</tr>
</tbody>
</table>

Table 4.1: Muscle Structure Design Information
Sample number 1 used five pointed oval shaped segments 180 mm in length and 75 mm in width. Once inflated this muscle structure was spherical in shape. It was similar in shape to a beach ball. This sample muscle had a significant amount of contraction. It contracted by 52.5 mm, which was 29.2%. In spite of the high level of contraction, it was clear that this shape of muscle structure would not be practical as the spherical shape would be awkward to be worn close to the body. To try and make the muscle structure less spherical and more oval shaped the next sample used six longer and thinner pointed oval segments, 200 x 50 mm. The inflated shape was less spherical, but it was still quite an impractical shape. This sample had good contraction at 20%. Sample number 3 used more segments, which were thinner in width, to try again to reduce the roundedness. This sample used eight pointed oval 200 x 35 mm segments. When inflated this gave a much more usable shape. It remained narrow, so it was the most suitable this far to be worn against the body. The disadvantage was that it had poor contraction. It contracted just 17.5 mm, giving just 8.75% contraction.

To try and achieve a high level of contraction a shape other than the oval which had been used so far was to be investigated. Inspiration was taken from the human skeletal muscle which has a large “muscle belly” which tapers away at both ends to create the characteristic spindle shape. To try and replicate this shape, segments that had a very wide but curved middle, which taper into narrow pointed ends were constructed. Sample 4, the first with this new segment design used five segments 170 mm in length and 65 mm at the widest middle point. When inflated this muscle contracted well with 20.6% contraction. The middle section of the muscle was the area that expanded the most on inflation, with the ends remaining quite narrow. Sample 5 built on the idea of having an exaggerated width of the muscle structure. This sample used five segments 200 x 75 mm. This sample also had a good amount of contraction at 20.0%. This idea was again developed further with sample 6. The segments used were not as curved in the middle as the previous two. These segments were almost diamond in shape. It used six segments 220 x 65 mm. This muscle structure did not contract as well as the previous two examples. It only exhibited contraction of 11.3%. The shape used in the segments for the muscles structure samples have created structures which although contracted well, had the disadvantage of an impractical shape. The wide middle section caused the muscle structure to be very bulbous. This design of muscle structure would not be able to be worn up against the body as they were too rounded.
In order to create a muscle structure which would be able to lie flat against the body, using segments of different shapes was considered. The possibility of creating the muscle structure with a flat side would enable the muscle to be worn against the body. To create a flat side it would mean that this area would not be able to expand on inflation; so another area would need to expand considerably to compensate. Sample 7 was designed to have large flat top and bottom areas which would have limited expansion, but with side areas with several narrow segments which would expand greatly on inflation giving good contraction. The top and bottom segments were 230 x 75 mm. This area was considerably wider against the narrow side sections, which were 230 x 35 mm. In total there were six of these narrow side sections, three on each side. When inflated the top and bottom segments of the muscle structure did remain relatively flat, with the side areas taking most of the expansion. This muscle structure performed well with 19.5% contraction. To try and encourage the top and bottom segments to remain even flatter, sample 8 used the same dimensions as the previous muscle structure, but used a double layer of fabric for the top and bottom segments. It was hoped that this added thickness would increase the stiffness of the segments so on inflation they would remain flatter. This did make a small amount of difference and the segments were slightly flatter, but it did affect the amount it contracted by. The contraction fell by over 4% to 15.2%. The design for sample 9 consequently used the idea of having one large segment to act as the flat base. Instead of having a large segment at the top to keep the top flat, this would have several narrow segments to form the shape of a longitudinally cut rugby ball once inflated. This muscle structure used a double layer base 230 x 105 mm and nine narrow segments 230 x 30 mm. When inflated the large bottom segment remained very flat and the narrow segments expanded into a dome shape. The contraction of this muscle structure was also good at 19.5%.

4.3 Seam Melding

From using the cotton fabric to create different shapes and designs of muscle structures it could be seen that with some more development, a suitable and efficient pneumatic muscle structure could be created. The next stage was to investigate whether a coated fabric could be used to create an air-tight single walled structure, rather than using an internal bladder. Not having an internal bladder would reduce hysteresis caused by dry friction, which is a
common problem with the McKibben PAM [21], [20], [49]. A thermoplastic coated fabric was chosen as this would enable the seams to be melded together. The fabric used was woven cotton with a PVC coating. As the purpose of this experiment was to see how well the seams could be melded together and how air-tight the overall structure would be, a basic design was used to simplify the production process. All of the muscles produced used five pointed oval segments 180 x 75 mm, sewn with the PVC sides together. This produced a muscle with the same dimensions as the muscle produced for sample 1. The details of the bonding methods for each sample are shown in Table 4.3.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Bonding Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Overlocked seams then ironed</td>
</tr>
<tr>
<td>11</td>
<td>Bonded plastic overlapped</td>
</tr>
<tr>
<td>12</td>
<td>Lockstitch seams then ironed</td>
</tr>
</tbody>
</table>

Table 4.3: Bonding Methods of Prototypes

For the first sample using the coated fabric, sample 10, the edges of the pieces were overlocked together in place. Using the hottest setting on a domestic iron, 200°C, the overlocked edges were melted into place by holding the iron over the seam for 5 seconds and then allowed to cool. This was sufficient to quickly melt the PVC layer on the fabric, which has a melting point of 80°C [3]. This high heat setting on the iron was used so the heat could penetrate the PVC, which was being protected by the cotton fabric, and also grease-proof paper, which was used to encase the muscle to prevent the PVC sticking to the iron. The seams stuck well. Any holes created by the sewing machine needle were filled with the molten PVC. Only one end of the muscle structure had been closed so it was difficult to
assess how air-tight the structure was.

The next muscle structure, sample 11 again used the same segment size. Seam bonding plastic adhesive was used in between the seams to be sealed. A $5 \text{ mm}$ strip of this plastic adhesive was placed in between the edges to be sewn, and then overlocked in place. The seams were melted in the same way. Again the seams adhered well. It was not clear if the additional seam sealing was necessary.

In sample 12 nothing was added in between the seams. The seams were sewn using a normal lockstitch with long stitches. It was thought that having less yarn around the seams may help with melt bonding the seams together. A long stitch length was used to reduce the number of holes punched into the fabric. To close the open end, a plastic tube was inserted into the open end and wire was wrapped around the neck of the muscle and the tubing to create an airtight seal. Using this tube air could be pumped into and sucked out of the muscle. The permeability of the seams could be tested this way. A small hand pump was attached to the tube and air was pumped into the muscle. The air pressure that this small pump produced was estimated to be in the region of $0.07 - 0.14 \text{ bar}$. The muscle cannot have been completely air-tight as the air pressure within the muscle slowly decreased. This slow loss of air pressure had to be minimised as the air supply reservoir in a practical application may be limited.

\section*{4.4 Seam Sealing}

It had been noticed that small cracks appeared at the joins of the seam where the PVC coating of the fabric had been pulled away from the backing fabric when under strain. To prevent this and to also increase air-tightness, a sealant was applied along the joins to plug any holes and reduce the strain along the seam. Silicone sealant was used as it is flexible and has good adhesion to textiles. The silicone sealant was experimented with to ascertain if it would be able to keep the muscle air-tight without the need to thermally meld the seam. The panels would just be sewn and then sealed using the silicone. For this sample, sample 13, the same sized panels, $180 \times 75 \text{ mm}$, as before were used. All the panels were sewn using an overlocking stitch, PVC sides together leaving a $30 \text{ mm}$ gap along the final panel seam. The muscle structure was turned inside out so the joins of the seam were now on the
outside. A plastic bag was inserted into the muscle to act as a bladder and was blown up to aid the application of the silicone. The silicone was applied along the joints of all the seams and allowed to cure for 24 hours at room temperature. Once cured the muscle structure was turned back in on itself so the silicone sealed seams were now on the inside. The final 30 mm gap was sewn up and silicone was applied along the seam joint through the small neck. Once cured, a tube was inserted into the neck and wrapped with wire to create an air-tight seal.

To find out if there was any advantage to which side of the coated fabric was sewn together, another sample, sample 14, was made. The same process as the previous sample was repeated but this time the panels were sewn fabric sides together. Consequently the silicone was applied to the cotton sides of the fabric.

Both muscles performed well and had a good air-tight seal. This showed that it may not be required to have the seams melded together, but for increased security it would be wise to meld the seams and seal them. The decision of which way up to sew the panels together may come down to which surface the silicone sealant adhered best to after many cycles of being inflated and deflated.

4.5 Valve

The inclusion of a valve into the muscle is required to create an airtight container, which can be inflated and deflated. A Schrader bicycle valve from a bicycle inner tube was chosen for the experimentation stage. The internal workings were removed so air could flow freely into and out of the valve. The valve was positioned in one of the panel walls as this would be simpler than positioning it at the end where the panels all meet, as this could cause complications with creating an airtight seal.

Two samples were made up using the same five 180 x 75 mm pointed oval segments as the previous samples. One sample, sample 15, had the coated sides sewn together; the other, sample 16, was sewn cotton sides together with a thermoplastic polyester web in between. They were both produced in the same fashion. The panels were sewn using an overlock stitch. A 40 mm gap was left for turning the muscle structure inside out along the sides.
of two of the joining panels. It was left at the side so the top and bottom could be sealed. The seams were melded for extra security. The muscle structure was turned inside out and silicone sealant applied to all the seam joins with extra applied at the top and bottom where the segments met. After the 24 hour curing, it was turned back to the right way round.

A small circular hole, large enough for the bicycle valve head and for a finger to fit in was cut in the panel opposite the muscle opening. The bicycle valve surrounded by a circular piece of the rubber inner tube was put into the muscle structure and the opening was sewn up and heat melded. Silicone sealant was applied over the newly sewn seam, through the circular hole made in the panel. Silicone was applied around the hole then the bicycle valve head was pushed through the hole and more silicone applied around the base of the valve head.

Using a valve allowed the air supply to be disconnected after inflating the muscle so air tightness could be easily judged. The muscle structure, which was sewn coated sides together, had better air tightness with only a minimal slow leakage of air. The sample sewn fabric sides together with the thermoplastic web between, still had a good amount of air tightness, but had a faster loss of air. This showed that it was more suitable to sew the PVC coated fabric coated sides together, and no further use of sewing the panels fabric sides together was used.

### 4.6 Kevlar “Tendons”

At this stage of development, the muscle structure was able to contract and relax with the introduction and removal of air but it was incapable of lifting or moving any load as a hooking point for this was not yet provided. Kevlar filament yarns were introduced into the seams of sample 17 by sewing it between the edges of the panels whilst being overlocked together. At each end the five Kevlar “tails” were plaited together to form a kind of tendon. Inspired by the way that biological muscles use tendons to attach themselves to bones, an attached load could be moved by being connected to the Kevlar tendon. An important role for the Kevlar in the seams was to improve the muscles stiffness along the length and help take the strain from the fabric by acting as a scaffold and to transfer the strain longitudinally. The presence of the Kevlar did not seem to affect the sealing of the seams and with the silicone also applied, gave as good air tightness as previous samples.
4.7 Rubberised Fabric

To preliminarily assess the strength and stability of the PVC fabric used so far for the muscle structure, a muscle was assembled from a stronger, more stable fabric, the kind used in camping air beds. It was woven cotton coated with a layer of rubber. This fabric was markedly stronger, thicker and more rigid. The sample, sample 18, was constructed using the same five pointed oval shaped segments 180 mm in length and 75 mm in width, sewn rubber sides together. Kevlar was sewn using an overlock stitch into the seams. As the melting point of rubber was too high to be reached on a domestic iron, it was decided that it was not necessary to use a thermoplastic web to bond the seams as the overlocking and silicone would be sufficient. The seams were sealed with the silicone sealant and a bicycle valve inserted. The following chapter records the results of testing of the muscle structures made from both fabrics, to assess which is a more suitable choice for further construction.

4.8 Conclusion

This chapter has discussed the early stages of development of producing a new type of PAM. Several different designs of artificial muscle had been proposed and basic contraction testing was carried out. This testing showed that the most contraction was produced when using a spherical-shaped muscle design. It was argued that this shape and the large size of the muscle was not practical to be incorporated into a muscle suit due to its bulbous nature. To try to resolve this problem several designs were developed which contained a flat side to the muscle. It was hoped that this flat side would fit well against the body. These designs however had low levels of contraction so were dismissed. The design that was taken forward and tested in the nest chapter is the spherical design. These tests measured the contraction and inflation of the muscle structure under different air pressure and whilst lifting various loads.

This chapter also covered the sealing of the seams. As the production of the muscle structures included having the seams sewn together, this caused the problem of puncturing the fabric, thus creating more areas for air to escape. Sewing the panels of the muscle structure together provided strong seams and a natural choice for joining the textile panels if the holes could be sealed. After several methods of attempting to make the seams air-
tight, using a silicone sealant along the seams had proved a successful method of creating a strong and flexible air-tight seal. The insertion of Kevlar along the length of the seams has acted as reinforcement, to transfer the strain along the length of the muscle structure and to allow attachment points for fixing the muscle structure into the muscle suit. The next chapter also uses the Kevlar tendons to attach different loads to, to test how well the muscle structure contracts under different loads.
Figure 4.1: Muscle Structure Samples 1 to 18
Chapter 5

Evaluation of Prototype Muscle Structure Properties

This chapter describes the experiments undertaken on the artificial muscle structures produced. These were preliminary experiments. As no artificial muscle structure of this kind had been produced in this style before, how it would perform in tests was unknown. Two areas were chosen for testing. As contraction is an important factor in an actuator, the contraction in terms of displacement was measured. The circumference of the muscle structures was also measured which represents the amount of inflation. From this the relationship between contraction and inflation could be studied. Measuring the circumference would also show how suitable the muscle structure was for wearing up against the body. The displacement and the circumference of the muscle structure were measured whilst bearing loads varying from 1.25 N to 50 N. The results were plotted on a series of graphs and the muscles constructed from different fabrics were compared.

5.1 Testing Rig

A testing rig, which can be seen in Figure 5.1, was set up consisting of a fixed arm attached to a clamp stand. The stand was encased in a box with polycarbonate screens for safety on the front and sides. A compressed air supply was fitted with a pressure regulator and a pressure gauge. The air supply was attached to the valve of the muscle structure as it hung from the fixed arm.
5.2 Testing Samples

Samples 17 and 18 presented in the previous chapter were tested using this air rig. These were spherical samples made from PVC coated cotton and rubber coated cotton, which had Kevlar yarns sewn in to their seams, which were sealed with silicone and had a Schrader valve fitted.

5.3 Displacement Testing

Muscle structures produced from PVC coated woven cotton and rubber coated woven cotton were tested to see how the load that they carried would affect the amount of contraction produced. Displacement was measured at 0.034 $\text{bar}$ intervals up to 0.35 $\text{bar}$ on contraction and relaxation to determine levels of hysteresis. The inflation stages of the muscle structure can be seen in Figure 7.1. Each test was repeated three times and an average taken. The results later in the chapter use the average result from the three tests.

5.4 Circumference Testing

The muscle structures produced from the two different fabrics were contracted and relaxed and the circumference of the middle of the structure was measured every 0.034 $\text{bar}$ on inflation up to 0.35 $\text{bar}$ and every 0.034 $\text{bar}$ on deflation. The effect of carrying different loads was investigated to see how it affected the circumference of the structure. As with the displacement testing, each test was repeated three times and an average taken. The results later in the chapter use the average result from the three tests.
5.5 Determination of Pressure vs. Extension Using PVC Coated Woven Cotton

Loads of 1.25 \(N\), 2.5 \(N\), 5.0 \(N\), 10.0 \(N\), 15.0 \(N\), 22.0 \(N\), 31.1 \(N\), 34.8 \(N\), 40.8 \(N\), 42.6 \(N\) and 50.0 \(N\) were hung from the Kevlar tendon of the muscle structure. The muscle structure was inflated to 0.35 \(bar\) at intervals of 0.034 \(bar\). At each 0.034 \(bar\) interval the height displacement of the load was measured in relation to the base of the testing rig. At 0.35 \(bar\), the air pressure was decreased back to 0.0 \(bar\) with intervals of 0.034 \(bar\) and the height displacement of the load measured again. Each load was measured three times and the average taken.
5.5.1 Results

Figure 5.3: Displacement of all the Loads with Median Load Highlighted of PVC Coated Muscle Structure
Table 5.1: Average Displacement in mm of the PVC Coated Muscle Structure, During Contraction and Relaxation Whilst Bearing Different Loads

![Figure 5.4: Displacement Vs. Load at 0.345 bar of PVC Coated Muscle Structure](image-url)
Table 5.2: Average Displacement in \textit{mm} of the PVC Coated Muscle Structure at +/- 0.034 \textit{bar}

<table>
<thead>
<tr>
<th>Load $N$</th>
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<th>15.0</th>
<th>22.0</th>
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Table 5.3: Percentage Contraction of the PVC Coated Muscle Structure at 0.345 \textit{bar}

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Figure 5.5: Displacement Vs. Load at 0.034 \textit{bar} of PVC Coated Muscle Structure

5.5.2 Discussion of Results

As can be seen on Figure 5.3 there was a general trend for the extension of the muscle structure to be reduced as the load it carried was increased. The total extension at a pressure of 0.35 \textit{bar} varied from 60.5 - 52.7 \textit{mm} over 1.25 - 50.0 \textit{N}. A 7.8 \textit{mm} decrease. It was the general trend for the extension to decrease with load, Figure 5.4 shows 1.25 - 2.5 \textit{N} had a lower total displacement at 0.35 \textit{bar} than loads 5.0 - 15.0 \textit{N}. The low loads not being able to extend the muscle structure to its full length before inflation begins can explain this.
The low loads were unable to overcome the stiffness of the fabric so the initial length of the muscle structure would be shorter than those with higher loads, the total displacement would therefore be less. Generally extension was inversely proportional to load.

The shape of the graphs produced as shown in Figure 5.3 was bi-linear. The majority of the extension was produced between 0 - 0.034 \text{ bar} for the low loads up to 5.0 \text{ N}. For the heavier loads most of the extension occurred between 0 - 0.07 \text{ bar}. It was up to this pressure that the muscle structure had inflated to near complete. After this pressure, came the second section of the graph. In this section, pressure increased to 0.35 \text{ bar} with a very high gradient as there was little more extension. Some of this extension must be credited to the small amount of stretch in the fabric. Loads 1.25 - 5.0 \text{ N} did not return to their original start height. Their load was too low to overcome the fabric’s stiffness. Loads 10.0 \text{ N} and over did return to their start height. As the loads increased, the faster the muscle structure returned to the original height after the air input was closed and the pressure reduced back to atmospheric. For 31.1 \text{ N} and over, the time taken for the muscle structure to return to its original height was less than one second.

The extension at 0.034 \text{ bar} for contraction and relaxation, followed a downward trend as load also increased, as can be seen in Figure 5.5. The extension at 0.034 \text{ bar} on relaxation was lower than the position on contraction. This was due to the hysteresis of the fabric. This ranges from 0.3 - 4.7 \text{ mm}. The most hysteresis occurred when the muscle structure lifted 50 \text{ N}. This was not what would be expected. More hysteresis would have been expected at the lower loads as it would be harder for these low loads to overcome the stiffness of the fabric. 40.1 \text{ N} shows the least amount of hysteresis at 0.3 \text{ mm}. The others range from 1.0 - 2.8 \text{ mm}.

5.6 Determination of Pressure vs. Extension Using Rubber Coated Woven Cotton

The same procedure for testing this muscle structure was performed as for the previous structure, which used the PVC coated cotton.
5.6.1 Results

<table>
<thead>
<tr>
<th>Load N</th>
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Table 5.4: Average Displacement in mm of the Rubber Coated Muscle Structure, During Contraction and Relaxation whilst Bearing Different Loads

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Table 5.5: Average Displacement in mm of the Rubber Coated Muscle Structure at +/- 0.034 bar

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<tr>
<td>% Contraction</td>
</tr>
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</table>

Table 5.6: Percentage Contraction of the Rubber Coated Muscle Structure at 0.345 bar
5.6 Determination of Pressure vs. Extension Using Rubber Coated Woven Cotton

5.6.2 Discussion of Results

The displacement of the muscle structures when using the rubber coated fabric at 0.35 bar varied from 63.2 mm to 57.0 mm; a 6.2 mm difference. The greatest amount of extension
was shown whilst lifting the 15.0 N load. The load of 42.6 N had the least amount of extension. These results are not completely what would be expected. It would have been expected that the lightest load of 1.25 N would have shown the greatest amount of extension.
and the 50.0 N load to show the least. Figure 5.7 shows how the results do not fall in a clean downwards trend. The extension at 0.35 bar when bearing 2.5 N and 15.0 N show serious deviation from the general trend. This same trend was shown in the PVC coated fabric, Figure 5.4, and can be explained in the same way. The lower loads were unable to straighten the muscle structure out to its full length, so the overall displacement was lower. In comparison to the PVC coated structure, which shows this trend up to loads of 5.0 N, the rubber coated structure shows anomalous results up to 15.0 N. The rubber coated fabric being stiffer can explain this. It therefore required a greater load to fully extend the structure and to expel all the internal air from the structure. As before, this graph shows general inverse proportionality.

Figure 5.6 shows that the muscle structure made from this fabric did not return to its original starting point after extension until the load of 15.0 N was lifted. This was 5.0 N greater than the load the PVC coated fabric required to return to zero extension. The greater load was required due to the higher stiffness of the rubber coated fabric. The shape produced in this graph again was bi-linear, but the second phase of the graph was not as steep as produced from the PVC coated fabric muscle structure. The lesser gradient of the rubber coated structure showed that the muscle contracts at a slower pace. Compared to the PVC coated fabric, the graph produced shows a much more even distribution of results and shows a higher amount of displacement. The second phase of this graph was less steep due to the fabric being stiffer and having less stretch than the PVC coated fabric. The muscle structure was less flexible meaning that it is harder to unfold and has very low stretch. The graph showed that at 0.034 bar there was an initially high level of contraction. This reflects the initial ballooning of the muscle structure to about 50% inflation. As the pressure is increased the contraction occurs much less rapidly. The contraction occurred slower as more pressure was required to fully unfold the muscle structure and as there was only minor stretching of the rubber coated fabric.

Figure 5.8 follows a downward trend. The result for 1.25 N did not conform to the other results. It showed very high extension at 0.034 bar on contraction and relaxation showing that the small load had little or no resistance to the inflation of the structure. The remaining results were spread over a much narrower range than the results for the PVC coated fabric structure. This showed that at these low pressures the fabric made from this stiffer rubber
coated fabric was more difficult to inflate than the more flexible PVC.

This fabric showed less hysteresis. There is a range from -0.8 mm to 2.3 mm. The greatest, 2.3 mm was shown at 1.25 N, which was to be expected, and the least, -0.8 mm was shown at 40.1 N. The remaining loads ranged from -0.5 mm to 1.7 mm. In general the hysteresis produced from this material was much lower than that of the PVC coated fabric.

Figure 5.9 shows the percentage the muscle structure of each fabric contracted from its original size (180 mm). The graph illustrates a downward trend showing how contraction generally decreased with the higher loads. It can be seen that the muscle structure that was made from the rubber coated fabric had a higher amount of total contraction than the structure made with the PVC coated fabric. It also showed a more consistent decrease in contraction with an increase in load. The rubber coated fabric ranged from the greatest amount of contraction of 35.1% at 22.0 N and the least of 31.7% at 42.6 N, a range of 3.4%. The PVC coated fabric had its greatest contraction at 5.0 N with 34.6% and its least at 50.0 N with just 29.3%, a greater range of 5.3%. The higher contraction rate of the rubber coated fabric showed that this muscle structure was able to cope with contraction at higher loads. The two fabrics vary in difference of contraction from 0% at 5.0 N to 2.7% at 50.0 N.

5.7 Determination of Pressure vs. Circumference using PVC Coated Woven Cotton

The same loads and the same procedure was undertaken for this experiment, but instead of measuring the height the load was displaced at each 0.034 bar interval, the circumference at the middle of the muscle structure was measured. Each circumference was measured 3 times for each load and the average calculated.
5.7.1 Results

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Table 5.7: Average Circumference in mm of the PVC Coated Muscle Structure, During Contraction and Relaxation whilst Bearing Different Loads.

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Table 5.8: Average Circumference in mm of the PVC Coated Muscle Structure at +/− 0.034 bar

5.7.2 Discussion of Results

Table 5.7 shows the variation in the circumference of the muscle structure ranged from 395.8 - 376.7 mm. This was a range of 19.1 mm. The greatest circumference of 395.8 mm was recorded when bearing loads 1.25 N, 2.50 N and 10.0 N. The smallest circumference of 376.7 mm was recorded at 50.0 N. Figure 5.11 shows how these results formed a general downwards trend in reduction of circumference with increasing load, showing that circum-
Figure 5.10: Circumference of PVC Coated Muscle Structure when Bearing all Loads with Median Load Highlighted

Figure 5.11: Circumference Vs. Load at 0.345 bar of PVC Coated Muscle Structure

Circumference was inversely proportional to load. The significant drop in circumference from 42.6 N to 50.0 N shows how the structure struggled to fully inflate under such strain. This was also illustrated in the position of the 50.0 N results line in Figure 5.10. It shows the large
5.7 Determination of Pressure vs. Circumference using PVC Coated Woven Cotton

Figure 5.12: Circumference Vs. Load at 0.034 bar of PVC Coated Muscle Structure

reduction of overall circumference throughout the whole range of pressures.

Figure 5.10 shows how the circumference results formed a bi-linear shape. For loads up to 40.8 N the majority of the inflation occurs between 0 and 0.034 bar, whereas for the heavier loads of 42.6 N and 50.0 N the pressure needed to be increased to 0.07 bar to obtain near complete inflation.

As with the extension testing, the second phase had a very steep gradient where little increase of circumference occurred at pressures between 0.07 and 0.35 bar. The positions of the results on the graph were all very close together showing that the load did not affect the overall circumference of the structure too radically. This graph also showed that the muscle structure did not return to its original starting circumference until loads of 10.0 N and over were applied.

Figure 5.12 shows that the difference in circumference from contraction to relaxation was minimal except for loads 42.6 N and 50.0 N. Very little hysteresis was shown with the other loads, ranging from -0.8 to 3.3 mm with several loads having 0 mm hysteresis.
5.8 Determination of Pressure vs. Circumference using Rubber Coated Woven Cotton

The same procedure for testing this muscle structure was performed as for the previous structure, which used the PVC coated cotton.

### 5.8.1 Results

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Table 5.9: Average Circumference in mm of the Rubber Coated Muscle Structure, During Contraction and Relaxation whilst Bearing Different Loads.

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Table 5.10: Average Circumference in mm of the Rubber Coated Muscle Structure at +/- 0.034 bar
5.8.2 Discussion of Results

The circumference of the muscle structure using this rubber coated fabric varied from 399.2 to 385.8 mm, a decrease of 13.6 mm. The greatest circumference was recorded whilst the structure was bearing the second lightest load of 2.5 N. The decrease in circumference
Figure 5.15: Circumference Vs. Load at 0.034 bar of Rubber Coated Muscle Structure was 5.5 mm less than that shown with the PVC structure. Except for the small jump in circumference at 2.5 N Figure 5.14 shows a downward trend and again shows how the circumference was inversely proportionate to load.

As with the comparison between the PVC and rubber coated fabric muscle structures when testing extension, Figure 5.13 showed a less steep second phase of the bi-linear format. This showed that less extension occurred in the first stage compared to the PVC structure showing that there was more increase in circumference in the second phase until the structure was completely inflated. The rubber structure also had a generally higher circumference at each load compared to the PVC structure.

Figure 5.15 shows some unexpected results. The circumferences at 0.034 bar on contraction and relaxation show large differences and cross over at several points. This differs from all the other graphs of the same style which generally showed the relaxation results to be a couple of millimetres above the contraction results and to follow the same general downwards path. The difference between the circumferences on contraction and relaxation varied from as little as -0.8 mm to as much as 16.7 mm. There was also no pattern to these results.
Chapter 6

Combined Muscle Construction Development

6.1 Introduction

Results from testing the prototype muscle structures gave good contraction rates but higher levels of contraction coupled with reduced muscle bulging would be preferable for easier integration with a garment. The work of Saga et al., which was discussed in Chapter 2.3.4 and the positive increase in contraction created when a ring was placed around the centre of their artificial muscle, influenced the development of the next stages of construction. The structures created by Saga and his team are cylindrical in shape when un-inflated but form two spherical structures when inflated. The mechanism of contraction in the structures created in this project was somewhat different and therefore a different approach was required. The approach investigated was the connection of muscles in parallel and tandem as explained below. Two smaller muscle structures linked together were created to see how the contraction properties alter.

Two spherical muscle structures, which were connected via a tube, was investigated. They were connected, so only one was needed to be attached to the air supply. It was unclear whether the secondary muscle would have a lower contraction rate, but it was hoped that they would both receive the same air pressures and obtain the same contraction properties. It was later proved that this was the case and both linked muscle structures inflated at the
same time. This experiment also showed how the size effected the contraction. As each muscle structure was 50% smaller than the previous samples, but as there would be two of them, the contraction properties could possibly be the same. The arrangement of the twin muscle structures was also investigated to determine if a series or parallel arrangement produced the greatest contraction.

6.2 Development of the Twin Unit Muscle Structure

The twin muscle structure was constructed using the same design as the larger spherical structures. Five oval panels 90 mm in length and 40 mm in width for each muscle structure were used for each small muscle using the PVC coated fabric. This design was used for ease of production and good contraction rates of the spherical design. Due to the small size of each of them; bulge was not such an issue. Each muscle structure was produced using the same construction techniques as the previous spherical structures. The segments were sewn with a length of Kevlar yarn in between and the seams were melded and then sealed with silicone. A set of rubber coated fabric muscle structures were also produced. These muscle structures were created using the same method as for the PVC coated fabric, except for one small difference. As the rubber coated fabric is unable to be melded along the seams, silicone alone was used to seal the sewn seams.

Two sets of twin muscles from each material were produced so one muscle set could be tested in parallel arrangement and one in series arrangement. This meant that when the second muscle was tested it was not affected by the cycles already completed by the previous set.

6.3 Testing of Twin Unit Muscle Structure Lifting

The two different fabric muscle structures were tested using the fixed arm test rig in either series or parallel arrangement. For the series arrangement the two muscle units were connected by knotting one Kevlar tendon from each unit together. One Kevlar tendon was attached to the fixed arm and one to the load. The series and parallel arrangements can be seen in Figure 6.1. The parallel arranged units were not joined and each unit had one tendon attached to the fixed arm and the other to the load. The muscle units were arranged
6.3 Testing of Twin Unit Muscle Structure Lifting

Figure 6.1: Twin Unit Muscle Structure in Series Arrangement on the Left and in Parallel Arrangement on the Right, Lifting 50.0 N

in a staggered formation so as not to affect the inflation of each other. Loads from 10.0 to 50.0 N were hung from the Kevlar tendon of the muscle structure. The muscle structure was inflated to 0.345 bar at intervals of 0.034 bar. At each 0.034 bar interval the height displacement of the load was measured in relation to the base of the testing rig. At 0.345 bar, the air pressure was decreased back to 0 bar with intervals of 0.034 bar and the height displacement of the loads measured again. This cycle was repeated for 3 cycles and the average taken.

Figure 6.2 shows the results from the twin muscle testing using the fixed arm rig. It can be clearly seen how the muscle units in parallel produced consistently higher contractions at all loads. The lower contraction levels in the parallel arrangement may be due to the Kevlar tendon inhibiting the full inflation of the lower muscle structure. This is illustrated in Figure 6.1. As expected the PVC coated fabric produced higher rates of contraction than the rubber coated fabric, a 27.2% maximum contraction compared to 22.4% maximum contraction when made from rubber. As with previous tests, the performance dropped more steeply with the PVC coated fabric as the weight increased and performed much more inconsistently than the rubber coated fabric. Although the rubber coated fabric yielded a lower contraction rate, the muscles show much less variation in the range of contraction and the curves are
smoother with a lower gradient. Some of the extra contraction that the PVC structures are able to produce is from the stretching of the fabric. The fabric had a moderate amount of stretch which was not desirable, as under inflation the cotton backing fabric would stretch and after several cycles the PVC would begin to crack along the seams. This caused a loss in air-tightness. These tests show how the twin muscle structures performed better in the series arrangement, up to 9.2% better in the rubber coated structure. Although the rubber coated fabric produced slightly lower contraction, the consistency and predicted superior performance at higher loads and the very low stretch in the fabric, meant the rubber coated fabric was only used for further development.

### 6.4 Production of a Triple Unit Muscle Structure

Leading from the success of the twin muscle system, a system using three muscle units was proposed. It was hoped that using the additional muscle unit that greater load lifting ability would be achieved. During the construction of the triple muscle structure a modular unit was developed. This consisted of a muscle unit with two valves attached to two opposing panels. One valve was the inlet/outlet valve for the pressurised air either coming from the compressor or from another muscle unit. The second was connected to the next muscle unit.
to allow air to pass into this unit. An end unit was required which only has one valve, which allows the passage of air to and from the previous muscle structure. Knotting the Kevlar tendons together joins the units. This format allows a string of small muscle structures to be joined together down to just a single unit, as shown in Figure 6.3. The limiting factor of this is the space available of the length of the upper arm, so either three or four units. This triple unit muscle structure was not tested using the fixed arm rig, but was tested using the moveable arm rig as described in the following sections.

Figure 6.3: Muscle Structure with Three Connecting Units with Detail of Top View
6.5 Arm Motion Testing

Previous experimental work studied the contraction of different muscle structure designs whilst bearing various loads. This testing method just showed the muscle structures static strength. As muscles rarely work like this in the human body a test to determine how the muscle structure reacted in a more life-like situation was developed. The objective of this experiment was to see how the muscle structures behaved when working to pull a lever (the lower arm); the loads that it would be able to lift to which angle, and the pressures required for lifting such loads. A structure to mimic the arm was produced with a low friction pivot to mimic the elbow. This arm was designed using anthropometric data for arm length as shown in table 6.1. The average (50th percentile) length of points on a female arm was used. This data was from a study of 19 to 65 year olds [58]. The rig produced is shown in Figure 6.4.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Men 5th percentile</th>
<th>Men 50th percentile</th>
<th>Men 95th percentile</th>
<th>Women 5th percentile</th>
<th>Women 50th percentile</th>
<th>Women 95th percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder - Fingertip Length (mm)</td>
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<td>780</td>
<td>840</td>
<td>655</td>
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<td>760</td>
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<tr>
<td>Shoulder - Elbow Length (mm)</td>
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<td>365</td>
<td>395</td>
<td>300</td>
<td>330</td>
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<td>475</td>
<td>510</td>
<td>400</td>
<td>430</td>
<td>460</td>
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<tr>
<td>Hand Length (mm)</td>
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<td>189</td>
<td>205</td>
<td>159</td>
<td>174</td>
<td>189</td>
</tr>
</tbody>
</table>

Table 6.1: Anthropometric Data for the Adult Arm [58]

The arm produced had a number of holes and hooks along the forearm and above and below the upper arm. This allowed the Kevlar tendons to be attached at different points along the forearm and at different distances above and below the upper arm. The different variations were tested to see how the different attachment point distances from the pivot (elbow) affected the contraction of the muscle and ultimately the angle created at the pivot due to the different moments involved. There was space to attach a muscle structure in the triceps position. The following testing would show if a muscle structure was needed or just a length of elastic or even nothing. The optimum positions for tendon attachment would be established, which would be the positions that created the greatest angles at the elbow at varying loads.
The positions of attachment of the twin and triple unit muscle structures in the biceps position above the upper arm to be tested were 40 mm, 80 mm and 120 mm above pivot level. The 40 mm position is about the distance from the centre of the humerus bone to the outside of the shoulder so should represent attachment at skin level. The positions of attachment along the lower arm to be tested were 45 mm, 70 mm and 95 mm and 120 mm from the pivot. This is shown in table 6.2. The muscle structures were attached to fixings in each of these positions and tested to find the optimum position of attachment. Figures 6.5 and 6.6 show the triple unit muscle attached to the arm rig in inflated and non-inflated positions.

<table>
<thead>
<tr>
<th>Horizontal Fixing Position mm</th>
<th>120</th>
<th>95</th>
<th>70</th>
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<tr>
<td>Vertical Fixing Position mm</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>120 / 40</td>
<td>95 / 40</td>
<td>70 / 45</td>
<td>40 / 45</td>
</tr>
</tbody>
</table>

*Horizontal fixing position describes the distance in mm from the pivot. Vertical fixing position describes the distance in mm above the line of the pivot at the shoulder position.*

Table 6.2: Positions of Attachment for the Muscle Units Above the Shoulder Position and Away From the Elbow Position

Initial investigations showed that the pressure required to lift the loaded lower arm was higher than that of the previous experiment. Pressures of up to 0.689 bar can be accom-
modated by the muscle structures but during initial investigating it was unsure whether the muscle structures would be able so sustain continual testing at these higher pressures, so initially pressures of up to 0.345 \( \text{bar} \) were recorded at intervals of 0.069 \( \text{bar} \). During an experiment to try to test the muscle structure to failure, it was seen that the muscle structure would not burst, but the silicone sealant on the seams would just fail and allowed air to escape. This was another reason for keeping the air pressure of this initial experiment low, as it was not wanted for the seams to become damaged.

Weights were attached to a hook on the end of the metal forearm in a position calculated using anthropometric table to simulate the position of the centre of the hand, where the palm meets the fingers. This was chosen as it is the area where loads are carried by humans. Initial tests showed that these muscle units were struggling to lift loads over 5.0 \( N \). For this reason only loads of 2.5 \( N \) and 5.0 \( N \) were attached to the moveable arm for testing.

Figure 6.5: Triple Unit Muscle Structure Attached in Bicep Position in Un-inflated, Relaxed State
6.6 Developments

6.6.1 Two Triple Unit Muscle Structures

The results from previous arrangement of using a triple unit muscle structure to flex the arm rig showed encouraging results. These results showed a range of movement between 18 – 46° with loads of up to 5.0 N. In order to achieve a greater flexion angle and the ability to bear greater loads two sets of triple muscle units working together were tested.

As Figure 6.7 shows, the muscle structures were attached to the vertical end plate on stacked top of each other. This was done due to the position of the original fittings on the rig. The positions of attachment of the muscle unit structures are shown in Table 6.3. These are different than the previous test attachment positions due to the attachment on the vertical base plate being in two positions.
Figure 6.7: Two Triple Unit Muscle Structures Attached in Biceps Position in Un-inflated, Relaxed State

<table>
<thead>
<tr>
<th>Vertical Fixing Position mm</th>
<th>Horizontal Fixing Position mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 / 80</td>
<td>120 / 120 / 80</td>
</tr>
<tr>
<td>80 / 40</td>
<td>120 / 80 / 40</td>
</tr>
</tbody>
</table>

*Horizontal fixing position describes the distance in mm from the pivot. Vertical fixing position describes the distance in mm above the line of the pivot at the shoulder position.*

Table 6.3: Positions of Attachment for the Muscle Units Above the Shoulder Position and Away From the Elbow Position
Figure 6.8: Angle Comparison of Twin and Triple Unit Muscle Structures with Loads of 2.5 N and 5.0 N at 0.345 bar
This arrangement allowed the muscle structures to bear weights up to 22.0 N and showed greater angles on flexion of 5.0 – 76.33°. As this arrangement has both strings of muscle units attaching at the same point on the forearm, this may have an effect on how well the third unit inflates on both the strings as they are being slightly squashed by each other. To avoid this, the rig was altered to allow the muscle structures to attach side by side without hindering each others inflation. Additional holes were drilled in the vertical back plate and two hooks were added overhanging from the forearm to allow the muscle structures to attach separately equal distance apart. Angles produced when using this arrangement ranged from 7.67 – 60.67° when lifting loads up to 22.0 N.

6.7 Results and Discussion

As previously discussed, the series arrangement of the muscle units contracted up to 4.4% higher than when in parallel arrangement. The experimental work using multiples of small muscle units were all conducted in series arrangement. Not all of the experimental work carried out in this project will be discussed. This results section will focus on the comparison of the twin and triple unit muscle structure and the comparison of the two configurations when using two sets of three muscle structures using the moveable arm rig.

As shown in Figure 6.8, there was no clear pattern to indicate which attachment point of the muscle structure yielded the best contraction. A pattern may have become clearer if more loads were tested, but the single string of muscle structures was not capable of lifting loads higher than 5.0 N. When two strings of muscle structures are attached to the rig, a pattern became clearer. As would be expected, the angles that the muscles are able to produce were reduced as the load increased. Angles produced ranged from 76.33° when lifting a 2.5 N load to 5.0° when lifting 22.0 N load, when in the stacked arrangement, and ranged from 60.67° when lifting a 2.5 N load to 7.67° when lifting 22.0 N, in the side by side arrangement. As Figures 6.9 and 6.10 show, the same results pattern occurred in both arrangements. It can be seen that the lower loads of 2.5 and 5.0 N performed better when attached nearer the elbow. The medium loads of 10.0 and 15.0 N performed quite similarly in all distances from the elbow, and the high load of 22.0 N gave the greatest contraction when attached furthest from the elbow and performed very poorly when attached close to the elbow. These results can be explained by the distance that the muscle structures are
6.7 Results and Discussion

Figure 6.9: Average Angular Displacement of Forearm by Triple Unit Muscle Structure with Various Loads and Different Attachment Points at 0.345 bar in the Stacked Arrangement

attached from the pivot and the load. When the muscles are attached close to the pivot, the highest amount of angular displacement can be produced as a small contraction in the muscle structures will yield a large movement at the end of the arm. When in this position, there is only a low amount of force able to be created, which is why as the load increased, the angular displacement of the arm decreased dramatically. When the muscle is attached
further away from the pivot and nearer the load, the same amount of contraction created in the muscle structures, will cause less angular displacement in the arm, but a higher amount of force can be generated. This is why the higher loads perform better when the muscle structures are attached nearer the load, as it is easier to lift the load as the distance from the pivot increases.

<table>
<thead>
<tr>
<th>Horizontal Fixing Position mm</th>
<th>120</th>
<th>95</th>
<th>70</th>
<th>45</th>
<th>120</th>
<th>95</th>
<th>70</th>
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<tr>
<td>Vertical Fixing Position mm</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>2.5 N</td>
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<td>53.00</td>
<td>60.00</td>
<td>69.33</td>
<td>57.00</td>
<td>58.67</td>
<td>66.00</td>
<td>76.33</td>
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<tr>
<td>5.0 N</td>
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<td>55.00</td>
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<td>55.00</td>
<td>62.33</td>
<td>60.67</td>
</tr>
<tr>
<td>10.0 N</td>
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<td>47.67</td>
<td>49.67</td>
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<td>15.0 N</td>
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<td>38.33</td>
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<td>42.00</td>
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<tr>
<td>22.0 N</td>
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<td>64.33</td>
<td>24.00</td>
<td>28.67</td>
<td>55.33</td>
<td>71.33</td>
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</table>

Table 6.4: Average Angular Displacement in Degrees of Forearm at 0.345 bar Under Different Loads and Muscle Attachment Positions when in the Stacked Arrangement

Figure 6.11 shows that the attachment points that gave the greatest angle of contraction at the lighter loads perform the least satisfactorily at the highest loads. The results range from 76.33° at 2.5 N to 5.0° at 22.0 N. These results were both from the stacked arrangement and from the same attachment point of 45 mm from the elbow and 80 / 40 mm from the shoulder. Those attachment points, which perform moderately well at low loads, only had a small drop in contraction angle at high loads.

As shown in Figure 6.12, attachment points, which performed worst at high loads, were those attached at 45 mm from the elbow. When the muscle units are attached 120 mm from the elbow, the least variation is shown when lifting the various loads. It also shows the worst performance at 2.5 N but the best performance when lifting 22.0 N. The most variation in angle is shown when the muscle units are attached 45 mm from the elbow. Attachment at this point gives the best performance at 2.5 N but the worst at 22.0 N. As this attachment point performs so poorly at higher loads it is not suitable to be used in a muscle suit, as the purpose of a muscle suit would be to aid movement and to assist in lifting loads.
Figure 6.10: Average Angular Displacement of Forearm by Triple Unit Muscle Structure with Various Loads and Different Attachment Points at 0.345 bar in the Side by Side Arrangement
Figure 6.11: Comparison of the Angular Displacement of Forearm by Both Arrangements of Triple Unit Muscle Structures with Various Loads Showing Different Attachment Points at 0.345 bar

Figure 6.12: Angular Displacement in Degrees of Forearm at 0.345 bar Under Different Loads and Muscle Attachment Positions when in the Side by Side Arrangement
Table 6.4 also follows the same trend as shown in Figure 6.12. It shows how as the attachment point comes nearer to the elbow pivot; the contraction angle increases at the lower weights, but decreases at the higher weights. This also means that the difference in angles created increases as the attachment point moves closer to the elbow. This is as was just described previously. The main difference between this table and Table 6.4 is the amount that the contraction drops is much greater in this table. The difference in angles created is up to $71.33^\circ$ with the other results being up to twice as high as many of the differences shown in Figure 6.12.

These results show that although the stacked arrangement does yield higher contraction at low loads, it produces very poor contractions at higher loads. This will be due to the muscle units closest to the elbow not being able to inflate fully due to their close arrangement. As the results from the side by side arrangement show a more consistent set of results at both high and low loads that this is the arrangement to be used in any further developments. Although it does not get such high contraction at the low loads, it will be more important to get reasonable amounts of contraction at high loads.

Although the attachment points of the muscle along the forearm show a pattern in both the stacked and side by side orientations, the results show a very mixed view of the shoulder attachment position. It is not clear which position gives the best overall performance at various loads. As a result, the position of the attachment point at the shoulder may be dictated by the attachment points possible on the final garment muscle suit.

### 6.8 Folded Panel Muscle Design

To try and improve on the current muscle design’s ease of production and increase the air-tightness of the seams, a muscle design with three panels was produced. Due to fewer seams it was proposed that it would be faster to produce and would have fewer weak points that could allow air to escape from. To allow for the reduced number of panels, the panel width was increased to produce a muscle with the same circumference as the previous five panel design. The panel size increase from $90 \text{ mm} \times 40 \text{ mm}$ to $90 \text{ mm} \times 60 \text{ mm}$. After seam allowance, the new circumference was just 1.24 $\text{mm}$ smaller than the five panel design. The new design was tested using the static lift rig to see how static contraction compared
with the five panel design. On testing it came apparent that although the circumference of
the three panel muscle was the same as the five panel muscle, it had much lower inflation.
This again was shown on the contraction results, shown in Table 6.5. This was due to the
reduction in volume. These show a range in contraction from 12.3 to 16.3 mm. This was at
least 5.7 mm lower contraction than the five panel design. The three panel design, which
used the new valve design, greatly improved on air-tightness and the muscle was almost leak
free.

As the three panel design had significant advantages over the five panel design, it would
be ideal if the three panel design could be developed to increase it’s inflation capabilities
and therefore contraction properties. To improve inflation a fold down the longitudinal axis
of each of the muscle’s panels would be incorporated. This would allow the fold to unfurl
during inflation and so increase the muscle’s internal volume and so hypothetically would
increase the muscle’s contraction. The design of the panels can be seen in Figure 6.13. The
pattern was created using the same 90 mm x 60 mm pattern, but allowed a 20 mm rectang-
ular channel to be added along the length of the panel. This was used to create the fold.
After folding, the width of the fold would be 6.6 mm. The finished folded muscle design is
shown in Figure 6.14.

Figure 6.13: Folded Panel Design Showing Fold Placement, dimensions in mm
After production, the muscle was tested using the static lift rig. As expected the fold in the muscle unfurled and it could be seen that the muscle have improved inflation and the results as seen Table 6.5, show a marked increase in contraction. Contraction ranged from 27.7 to 33.7 \textit{mm}, this was at least 5.7 \textit{mm} more than the five panel design and at least 11.4 \textit{mm} more than the non-folded three panel design. The incorporation of a fold greatly increased the contraction of the muscle; next it was tested to see if the size of the muscle could be reduced. If muscle contraction and strength were not too heavily compromised, it would be advantageous for the reduction in size as would be easier to incorporate into a garment. If the muscle size could be reduced it may allow for an increase in the number of muscle that can be joined together. This should balance out any reduction in muscle strength or contraction.

<table>
<thead>
<tr>
<th>Muscle Design</th>
<th>Load N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td>5 Panels</td>
<td>19.7</td>
</tr>
<tr>
<td>Volume approx. 9.1 cm\textsuperscript{3}</td>
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<td>3 Panels</td>
<td>12.3</td>
</tr>
<tr>
<td>Volume approx. 7.6 cm\textsuperscript{3}</td>
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</tr>
<tr>
<td>3 Folded Panels</td>
<td>31.7</td>
</tr>
<tr>
<td>Volume approx. 19.2 cm\textsuperscript{3}</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.5: Contraction in \textit{mm} of Different Muscle Designs Lifting Different Loads at 0.345 \textit{bar}
6.8.1 Folded Panel Size Reduction

In comparison to the previous muscle design using five panels, this new folded three panel design was much larger and bulkier. As the design proved to have increased contraction properties, the problem with the size needed to be addressed. Two muscle structures were produced using the same design method as described in Figure 6.13, but they were reduced in size by 10 and 20%. The width of the fold was kept the same, but the length and width at the centre of the panel was reduced in size. The muscle structure, which was 10% smaller, had dimension of 81 x 72 mm and the 20% smaller structure had dimension of 72 x 64 mm. These dimensions produced a much more suitable sized muscle structure. Table 6.6 and Figure 6.15 show how the reduction in size of the muscle structures affected the contraction. It can be seen that both of the structures perform similarly at lower loads, both contracting around 22 mm, but the 50.0 N load, the muscle structure that is 20% smaller performs very slightly better, with a 1 mm greater contraction. It can be seen in Figure 6.15, that the displacement created by the muscle structures was related to their volume. The muscle structure with 3 folded panels had the greatest contraction as it had the largest volume. As this design had its size reduced, the volume decreased, as did the contraction created. The non-folded 3 panel muscle structure had the smallest volume, and yielded the lowest contraction. In order to choose which size of muscle structure is most suited to further development in this project, the performance, aesthetic qualities and ease of production will be taken into account. The 10% smaller panel length produces a muscle structure with high levels of contraction but it was quite bulky. The panel size 20% smaller does produce good levels of contraction, but it is very difficult to produce due to its small size. As a compromise, a panel 90 x 70 mm was decided on. This produces good levels of contraction across all loads without being too bulky. This is a suitable size and for both incorporation into a garment and ease of production.

6.9 Anchor Point

In order to increase the angular motion of the arm during the inflation of the muscle structures, it was proposed that the string of muscle structures could be anchored to a point at the elbow. This anchor point would allow free movement of the Kevlar tendons during their movement on inflation and deflation. The string of spherical muscle structures produced
<table>
<thead>
<tr>
<th>Muscle Design</th>
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<th>15.0</th>
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Table 6.6: Contraction in mm of Different Muscle Designs Including Reduced Sized Folded Structures, Lifting Different Loads at 0.345 bar

Figure 6.15: Load vs. Displacement of Muscle Designs Including Reduced Sized Folded Structures at 0.345 bar

from five panels would be able to be attached at points on the shoulder and the wrist. Without the anchor point, these attachment points would allow the muscles to lift the arm with low effort, due to the long distance from the elbow pivot. This arrangement would cause aesthetic and comfort issues, as the string of muscles would project a long distance from the natural bend of the arm when the muscles are inflated. This would also hinder
natural movement of the arm and body. With the anchor point in place the angular contraction should be increased and the string of muscles will follow the natural curve of the arm. A disadvantage will be that a high amount of force will be generated at this point. Bracing, or some type of rigid joint would have to be incorporated into the suit. The five panel design was used in this test due to the availability of the design. These results still give a good representation of how the three folded panel design responds.

### 6.9.1 Testing of Single String With Three Muscle Structures

The string of three muscle structures was tested using the arm motion testing rig. The set-up of the rig was the same as discussed in chapter 6.5. The only difference was that two muscle units were located on the upper arm section and one on the lower arm section. A longer Kevlar tendon was used to join the upper and lower arm muscle units. The arrangement was tested to see what the comparison was between angular contractions with and without the anchor point.

#### Results and Discussion

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Table 6.7: Average Angular Displacement of Single String of Three Muscle Structures with Attachment Points in the Shoulder and Wrist Position, During Contraction and Relaxation Whilst Bearing Different Loads in Horizontal Arrangement

The results of the testing when the string of muscles were not anchored at the elbow shows a consistent level of contraction of around $30^\circ$ up to loads of 7.5 $N$. This can be seen in Table 6.7. Loads heavier than this were unable to be lifted. Table 6.8 shows the
Table 6.8: Average Angular Displacement of Single String of Three Muscle Structures with Attachment Points in the Shoulder and Wrist Position, During Contraction and Relaxation Whilst Bearing Different Loads with an Anchor Point at the Elbow in Horizontal Arrangement

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Figure 6.16: Pressure vs. Angular Contraction of Triple Unit Muscle Structure Without Anchor Point in Horizontal Arrangement

results when the string of muscles was anchored at the elbow. It can be seen that it had a distinctly higher angular contraction at lower loads, but as the load increased, the angular contraction dropped steeply. The arm was unable to be lifted past loads of 5.0 $N$; this was notably lower than the arrangement with no anchor. When the arm lifted no load, the lower
Figure 6.17: Pressure vs. Angular Contraction of Triple Unit Muscle Structure with Anchor Point in Horizontal Arrangement

Figure 6.18: Pressure vs. Angular Contraction of Triple Unit Muscle Structure with and Without Anchor Point at 0.345 bar in Horizontal Arrangement
arm was raised $95^\circ$. The actual angle that the arm could have been lifted could have been greater, but there is a metal bar on the rig that prevents the arms being raised past $95^\circ$. If the arm were raised further than this the arm would just fall towards the shoulder due to gravity if the lower arm weighed more that the load being lifted.

Figures 6.16 and 6.17 show the different contraction styles of the two arrangements. It can be seen that when the muscle structures are not anchored at the elbow, contraction begins at lower pressures than when the structures are anchored. This is because the force required to lift the loads is lower when the muscle structures are pulling directly near the end of the lower arm. As previously mention, this explains why the non-anchored arrangement can lift higher loads, but overall yields lower angular displacement than the anchored arrangement.

Figure 6.18 confirms how the anchor point gives the arrangement much higher contraction at low loads, but as the load increases, its performance sharply deteriorates and performs worse than the arrangement with no anchor point. The arrangement with no anchor point has results that range by $13^\circ$, whilst the arrangement with the anchor point has a range of $71^\circ$.

In spite of the wide range of the results given from the arrangement with the anchor point, it still is viable to pursue this arrangement due to the high angular contraction achieved at low loads. This level of contraction is at least $18.66^\circ$ greater than has been achieved before in various arrangements. To try and increase the load bearing capacity of the arrangement, two strings of three muscle units will be tested.

6.9.2 Testing of Double Strings With Three Muscle Structures

The muscle structures were arranged as in chapter 6.5, but again the third muscle unit was positioned on the lower arm. As before a control test with no anchor point was completed, then the arrangement with the anchor point was tested.
Table 6.9: Average Angular Displacement of Two Strings of Three Muscle Structures, During Contraction and Relaxation whilst Bearing Different Loads in Horizontal Arrangement

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Figure 6.19: Pressure vs. Angular Contraction of Two Sets of Triple Unit Muscle Structures Without Anchor Point in Horizontal Arrangement

Results and Discussion

As with the single string arrangement, Table 6.9 shows that the unanchored results had a very consistent rate of contraction. This can also be seen in Figure 6.19. The angle of the arm on contraction was again around 30°. The results range from 29° to 36°, and loads up to 17.5 N were successfully lifted. This was very similar to the results from the single string arrangement, but higher loads could be lifted. This showed that this arrangement, indepen-
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Table 6.10: Average Angular Displacement of Two Strings of Three Muscle Structures, During Contraction and Relaxation whilst Bearing Different Loads with an Anchor Point at the Elbow in Horizontal Arrangement

Figure 6.20: Pressure vs. Angular Contraction of Two Sets of Triple Unit Muscle Structures with Anchor Point in Horizontal Arrangement

dent of the number of muscle units used, angular contraction will never extend beyond 40°, and therefore not be a suitable arrangement for further study.

Table 6.10 shows the angular contraction results of two strings being anchored at the elbow. As with the single string testing results, it shows very high angular contraction at low loads, and a steep drop in contraction as the loads increased. The angles produced
ranged from $95^\circ$ to $7^\circ$ with loads of up to 17.5 $N$ being lifted. This wide range of results can be seen in Figure 6.20. As before, the arm was prevented from lifting further than $95^\circ$, but if it had not been restrained it would have achieved a greater angular contraction when lifting both no load and 1.25 $N$. Although angular contraction decreased greatly, it did so less sharply than when the single string was used. Figure 6.21 compares the contraction at 0.345 $bar$ and it can be seen that the single string with the anchor point has a greater gradient than when two strings are used. This graph also shows that at loads higher than 15.0 $N$, the arrangement with the anchor point performs less well than when there is no anchor. Even when taking this into account, it seems valid to say that the overall the anchor point improves the angular contraction of the arm and is a good arrangement to further use and develop. Having the muscle structure anchored at the elbow also makes the profile of the arm more aesthetically pleasing and less obstructing to body movement.

6.9.3 Conclusion

It can be seem from the results that when the muscle structures were anchored, higher levels of angular contraction were recorded. When the muscle structures were not anchored they had a very consistent level of contraction. The amount of contraction they achieved
was consistently around 30°. Due to the length of the muscle string and the maximum contraction of the muscle structures, this was the maximum contraction this arrangement was able to achieve. Even when the air pressure was increased to investigate if this was the most contraction able to be produced, no extra contraction occurred. The levels of contraction did fall steeply when not anchored and produced low levels of contraction at high loads, but the high levels of contraction at low loads and the more body functional arrangement means it was hard to dismiss this arrangement. In-situ testing was needed to be carried out to ascertain if this arrangement was safe to be used. If the force on the elbow was too high or it was not capable of lifting the weight of a human arm plus an extra load, a new arrangement would have to be fitted. The next section of this chapter will look at changing the arrangement of the rig so it was able to test the lifting ability of the arm in a vertical arrangement. This would provide a more realistic impression of the movement of a human arm.

6.10 Testing of Vertical Arm Set-up

Currently the testing of the angular contraction of the muscle structures has taken place horizontally as shown in Figure 6.6. In order to examine how gravity will affect the contraction, the rig was altered so the arm would have to be lifted vertically. This can be seen in Figure 6.22. The same tests were carried out as previously discussed in chapter 6.9. In these tests though, pressures of up to 0.689 bar were used. Previously only 0.345 bar was used as it was thought that the muscle structures might not be able to cope with higher pressures. The muscle structures currently used were able to cope with higher pressures, and as a result gave higher contraction levels. The angular contraction was measured with a single string of three muscle structures, then a double string. The same tests were then repeated with the string of muscle being anchored at the elbow. Figures 6.23, 6.24, 6.25, and 6.26 show photographs of the muscle structures arrangement on the vertical rig. As with the horizontal testing the muscle structures were unable to lift as high loads when static lifting. In this test, loads of up to 30.0 N were used and 90 x 70 mm folded three panel muscle structures.

When the muscle structures were attached to the vertical arm rig, the lower arm did not hang totally vertical i.e. the recording did not start at 0°. The following results have all
been altered so they start at zero and show the total angular displacement.

Figure 6.22: Vertical Arm Arrangement Showing Triple Muscle Structure Attached
6.10 Testing of Vertical Arm Set-up

Figure 6.23: Vertical Arm Arrangement Showing Inflated Triple Muscle Structure Lifting the Arm

Figure 6.24: Vertical Arm Arrangement Showing Inflated Triple Muscle Structure, Anchored at the Elbow Lifting the Arm
Chapter 6: Combined Muscle Construction Development

Figure 6.25: Vertical Arm Arrangement Showing Inflated Two Triple Muscle Structures Lifting the Arm

Figure 6.26: Vertical Arm Arrangement Showing Inflated Two Triple Muscle Structures, Anchored at the Elbow Lifting the Arm
6.10.1 Single String Testing Results and Discussion

Figure 6.22 shows the un-inflated triple muscle structure. Figures 6.23 and 6.24 show the results of inflation. It can be seen that when the string of muscle structures was anchored at the elbow, the arm was lifted to a greater extent. By studying tables 6.11, 6.12 and Figure 6.29 it can be seen that at low loads the anchored muscle string produced higher angular contraction, the highest being with no load, which produced a 54.0° displacement at 0.689 bar, compared to the 34.0° displacement at 0.689 bar when unanchored. As the load was increased, the anchored muscle string rapidly decreased the amount of contraction produced, and at loads past 5.0 N the unanchored muscle string produced greater displacement. The unanchored muscle string produced a more steady level of displacement. The displacement did decrease as the load increased, but over a smaller range than the anchored muscle string. The unanchored muscle string produced displacement from 34.0° to 17.0°, a range of 17°. In comparison, the anchored muscle string had a displacement range from 54.0° to 12.0°, a range of 42.0°. It can be seen from Figures 6.27 and 6.28, that in comparison to the horizontal testing arrangement, when in the vertical testing arrangement, the anchored and non-anchored arrangements had the same contraction characteristics. They both produced angular displacement at the lowest air pressure, and showed the greatest amount of displacement also at low air pressures. From the low levels of displacement produced by the single string of muscles, the use of just one string was ruled out. It was also wanted to see how the distance that the muscle strings were anchored from the pivot point, or elbow would effect contraction. As it was decided that one string of muscle structures would not be sufficient for use in a practical application, this was only tested when using two sets of muscle structures. The next test shows the effect of the distance of the anchor point from the pivot.
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Table 6.11: Average Angular Displacement of a Single String of Three Muscle Structures without Anchor, During Contraction and Relaxation whilst Bearing Different Loads in Vertical Arrangement
6.10 Testing of Vertical Arm Set-up

Figure 6.27: Pressure vs. Angular Contraction of a Single String of Three Muscle Structures without Anchor, During Contraction and Relaxation whilst Bearing Different Loads in Vertical Arrangement

Figure 6.28: Pressure vs. Angular Contraction of a Single String of Three Muscle Structures Anchored at the Elbow, During Contraction and Relaxation whilst Bearing Different Loads in Vertical Arrangement
Table 6.12: Average Angular Displacement of a Single String of Three Muscle Structures Anchored at the Elbow, During Contraction and Relaxation whilst Bearing Different Loads in Vertical Arrangement

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Figure 6.29: Angular Displacement Vs. Load of Single Muscle Structure Arrangements at 0.689 bar
6.10.2 Double String Testing Results and Discussion

Tables 6.13 and 6.14 show the angular displacement results of the double string testing. It can be seen that as expected the displacement produced is higher than that those using the single muscle string. The highest amount of contraction was recorded when the anchor point was used with no load. This produced a displacement of 66.0° at 0.689 *bar*. As with the single muscle string, the displacement produced when the double string was anchored at the elbow decreased quite rapidly when the load was increased. Figures 6.30 and 6.31 show how again, as with the single string, the anchored results are spread over a larger range than the non-anchored results. This again shows the effect of having the force acting nearer the pivot in the anchored arrangement. Figure 6.32 shows how this decrease was at a lower gradient showing a more steady displacement decline. The unanchored double muscle string shows a very constant level of displacement. The displacement with no load was 36.0°, and at a load of 30.0 *N* was 30.0°, a range of 6.0°. The unanchored double muscle string produced higher levels of displacement after the load of 10.0 *N*.

Figure 6.33 shows the angular contraction produced by the muscle structures at 0.689 *bar* when the strings were anchored at various distances from the pivot. The distances used from the pivot were 2 cm, 3 cm, 4 cm and 5 cm. This was done to see how the distance from the pivot affected the contraction. It can be seen that the greatest contraction was produced when the muscle strings were anchored 2 cm from the pivot. A angular displacement of 70.3° was produced when lifting no load. With a load of 1.25 *N* a high contraction was also produced of 62.3°. When the load is increased to 2.5 *N*, it can be seen that the displacement dramatically drops to 42.0° and then continues to show the lowest contraction of all test samples. As the distance that the strings were anchored, the results become inverted. This results in when the strings are anchored furthest from the pivot, 5 cm, the displacement is the lowest of the samples when lifting no load, with a displacement of 56.7°. When lifting 20 *N* it shows the highest amount of contraction at 27.3°. This shows that when attached near the pivot, there is higher contraction, but lower total lift. Overall it would be best to anchor the muscle structures further from the pivot to get higher levels of lift at higher loads.
Table 6.13: Average Angular Displacement of Two Strings of Three Muscle Structures without Anchor, During Contraction and Relaxation whilst Bearing Different Loads in Vertical Arrangement

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Figure 6.30: Pressure vs. Angular Contraction of Two Strings of Three Muscle Structures without Anchor, During Contraction and Relaxation whilst Bearing Different Loads in Vertical Arrangement
### 6.10 Testing of Vertical Arm Set-up

#### Table 6.14: Average Angular Displacement of Two Strings of Three Muscle Structures Anchored at the Elbow, During Contraction and Relaxation whilst Bearing Different Loads in Vertical Arrangement

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Figure 6.31: Pressure vs. Angular Contraction of Two Strings of Three Muscle Structures Anchored at the Elbow, During Contraction and Relaxation whilst Bearing Different Loads in Vertical Arrangement
Chapter 6: Combined Muscle Construction Development

Figure 6.32: Angular Displacement Vs. Load of Various Muscle Structure Arrangements at 0.689 bar

Figure 6.33: Angular Displacement Vs. Load of Various Muscle Structure Arrangements at 0.689 bar Anchored at Various Distances from Pivot
6.10.3 Conclusion

The vertical arm testing overall showed a lower amount of contraction than its comparative test when horizontally arranged, even though pressure of up to 0.689 bar and muscle structures with a greater volume were used. The need for additional air pressure shows how the effect of gravity puts extra strain on the muscles. Considering the folded 90 x 70 mm muscle design is capable of greater contraction than the five paneled design used for horizontal testing, the vertical testing of the muscle structure proved a more difficult task. The reduction can be accounted by the gravity acting on the vertical arm. The tests have shown that as with the horizontal testing, when the strings of muscle structures are unanchored, the amount of contraction remains relatively constant. This showed that even at high loads, the muscle structures were contracting to their actual or near maximum.

Both anchored and unanchored arrangements produced higher levels of contraction than their single string counterparts. This is further evidence to no longer continue investigating the single string arrangement. The slower decline in contraction as the load was increased on the anchored double string compared to the anchored single string, and the higher loads the double anchored string arrangement was able to lift add confidence in using this arrangement in the final muscle suit design. The anchored arrangement was clearly more aesthetically pleasing and easier to incorporate into a garment with a more appealing look. This arrangement would also not impede other bodily movements so could be more comfortable for the user to wear.

6.11 Final Muscle Structure Design

Following the stages of design and development and the testing of these prototypes, a final design for a PAM has been developed. The PAM is produced using three panels each 90 x 70 mm, with a fold with a width of 10 mm. The edges of the panels are sewn together using a overlocking stitch. A length of Kevlar is sewn between the seams. The seams are sealed using a line of silicone sealant and a pneumatic elbow valve is fitted. Three of these muscle structures are linked together. They are connected by using three double lengths of Kevlar sewn into a seam of each of the three muscle structures. The Kevlar is plaited in between each of muscle structures. The three muscle structures are arranged in a staggered format. This allows for two of the structures to be in the position of the upper arm, and
a single muscle structure to be in the lower arm position. Two of these strings are used to provide additional strength and angular contraction. Figure 6.34 shows the final design and arrangement of the PAM. The total mass of the string of muscle structures, including five valves is, 185 g.

Figure 6.34: Final Design and Arrangement of the Pneumatic Artificial Muscle

6.12 Comparison Between Vertical Arm Testing and Static Testing

In order to compare how the static testing of the muscle structure, as shown earlier in this chapter, with the vertical arm testing, a mathematic calculation was derived which would calculate the force acting on the muscle when is was incorporated into the arm arrangement. The amount of contraction that the muscle created when in this arrangement could then be compared to the amount of contraction created when in a static arrangement (i.e. when the load was directly attached to the muscle), when the same amount of force was acting on both of the muscles. The results for the static lift had already been collected, so just the vertical arrangement results needed to be collected. To do this the vertical arm testing experiment was carried out using only one muscle structure. The muscle structure was inflated up to an air pressure of 0.35 bar, the same pressure used on the static testing. Loads of up to 10 N were attached to the end of the lower arm and the contraction of the muscle structure between two fixed points was measured. To calculate the force acting on the muscle structure whilst in the vertical arm arrangement to hold a certain load at a certain angle, the following equation was used:
6.12 Comparison Between Vertical Arm Testing and Static Testing

\[
Force = \frac{(Lower\ Arm Mass \times g)(\frac{1}{2} CB) \sin \theta + (Load \times g) CB \sin \theta}{CE}
\]

The letters in the equation relate to the points on the arm rig as shown in Figure 6.35. This figure shows the movement of the arm as the muscle structure inflates. It can be seen that length AB decreases as the muscle structure inflates. It can be seen that as AB decreases, CE also decreases. The line CE was created as an extension of AD in order to create a right angle opposite the pivot. The equation was divided by CE as it will represent how much the pivot assists the movement. CE was used rather than CD as the force of a moment arm should be measured perpendicular to the vector. The results of these lengths at different pressures, along with the result if the equation can be seen in Figure 6.36.

![Graphical Representation of Un-Inflated (left) and Inflated (right) Single Muscle Structure When in Vertical Arm Set-Up](image)

**Results**

Figure 6.36 shows the results of several readings taken from the vertical arm testing. The internal angle, the angular displacement and the muscle structure displacement were measured every 0.7 bar at loads up to 1.0 Kg. It can be seen that the internal angle never started at 180°, due to the initial tension in the system to prevent wasted contraction. From knowing the internal angle of the arm and the lengths of the upper and lower arms,
the set-up was drawn in scale. This allowed CE to be calculated. It can be seen that as the pressure increased in the muscle structure, and the arm was raised, CE decreased slightly, then increased as the arm was lowered.

It can be seen that equation results follow the same pattern for all of the loads. It shows that as the pressure increased in the muscle structures and the arm is raised, more load was acting on the muscle structure. The amount increased due to less of the load of the lower arm and attached load was shared by the pivot. When the arm was hanging vertically, or near vertically, the majority of the load of the arm and attached load will be transferred through the pivot, so the load acting on the muscle structure was lowest. As the arm was raised, less of the load would be transferred through the pivot. If the arm ever reached 90°, the pivot would be sharing the least amount of the load so the force required would be the greatest.

Figure 6.37 shows the relationship between the load attached to the end of the arm and the load acting on the muscle. It can be seen that as expected, the higher the air pressure, the greater the load acting on the muscle structure. As the graph is slightly curved, it may be seen that the relationship between load on the arm and the load acting on the muscle structure is not fixed. When a 1.25 N load was attached to the end of the arm, it can be seen that the load acting on the muscle structure varies from 4.2 N at 0.069 bar, to 5.9 N at 0.345 bar. This is 3.3 to 4.7 times higher than the load attached to the arm. This multiplication factor decreases as the load is increased. When 5 N is attached to the arm, the load acting on the muscle structure was 2.1 to 3.3 times higher. This decreased to 1.5 to 2.4 times higher when 10N was attached to the arm.

Figure 6.38 shows the relationship between the load attached to the end of the arm compared to the angular displacement created. As would be expected, the angular displacement increased, as the air pressure inside the muscle structure was increased, but the angular displacement decreased as the load at the end of the arm was increased.
## 6.12 Comparison Between Vertical Arm Testing and Static Testing

### Figure 6.36: Table of Results of Mathematical Modelling

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<td>7.0287</td>
<td>0.0</td>
<td>167.0</td>
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<td>167.0</td>
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<td>7.0287</td>
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<td>167.0</td>
<td>0.00</td>
<td>0.0600</td>
</tr>
</tbody>
</table>
Figure 6.37: Load Acting on the Muscle Vs. Load at Attached to End of Arm at Various Pressures

Figure 6.38: Angular Displacement of the Arm Vs. Load at Attached to End of Arm at Various Pressures
Figures 6.39, 6.40 and 6.41 compare the length of the muscle in relation to the load acting on it. The length of the muscle reflects how much the muscle had contracted. The starting length of the muscle was 90 mm, so the smaller the length shown on the graph, the more the muscle structure had contracted. It can be seen that when the muscle structures were being inflated to 0.069 bar, there was a wide variation in muscle length. The muscle in the static arrangement was capable of greater contraction, which became magnified as the load was increased. As the pressure was increased, the contraction of the muscle under lower loads became more similar. At high loads the muscle structure in the arm arrangement had a steeper reduction in contraction than the static arrangement. The difference in contraction of the muscle structure in the arm compared to the static arrangement may be due to friction around the anchor point. In the arm arrangement, the Kevlar “tendon” travels under the anchor point at the elbow. The equation assumes that there was no friction occurring, but in reality there may be. The Kevlar “tendon” was anchored by a Kevlar loop attached to the pivot. This may have created friction between the loop and the Kevlar “tendon” which could explain the reduction in contraction in the arm arrangement.

Figure 6.39: Muscle Length Vs. Load Acting on Muscle with Various Loads at 0.069 bar
Figure 6.40: Muscle Length Vs. Load Acting on Muscle with Various Loads at 0.207 bar

Figure 6.41: Muscle Length Vs. Load Acting on Muscle with Various Loads at 0.345 bar
Chapter 7

Modelling of Pneumatic Muscles

7.1 Nomenclature

\( g \) : Acceleration due to gravity, 9.81\( \text{m/s}^2 \)
\( l \) : Total length of thread / muscle
\( m \) : Mass being supported
\( T \) : Tension in the thread / muscle at a point
\( z \) : Distance along the thread measured from the bottom at \( z = 0 \)
\( \theta \) : Angle of the thread / muscle wall at a point
\( F \) : Force
\( p \) : Pressure
\( x, y \) : \( x \) and \( y \) coordinates

7.2 Introduction

This chapter focuses on the modelling of the muscle structure. The shape and curvature of the muscle structure that will be created under specified loads and pressures were modelled. It also predicted the amount and rate of contraction the muscle produced. The theoretical predictions could then be compared to the actual results. Several different stages of modelling had been worked through. These will be described below.
A number of assumptions have been made to help with the modelling. These are:

- Tension acts equally along the length of the muscle;
- The fabric does not stretch;
- The fabric is of uniform thickness and composition;
- The attachment points for the muscle and the Kevlar tendon are of negligible area;
- Curvature of the muscle is caused by the suspended weight.

The aim of the modelling was to predict the amount of contraction and the curvature of the muscle structure during inflation that would represent the findings of the actual test, as shown in Figure 7.1.
7.3 One Point Force Modelling

The first step of modelling was to see how much the muscle contracted when a force was only acting at one point. The area of the muscle was not considered, as it was assumed that the force was acting on a string rather than the 3-dimensional spherical muscle. The end position of the string attached to the load was to be found. This position would therefore show the displacement of the load. Figures 7.2 to 7.4 show the forces acting on the piece of string.

![Diagram of forces and tensions acting on the string](image_url)

Figure 7.2: Forces and Tensions Acting on the String
Vertically:

\[ mg = 2T_1 \sin \theta \]

as

\[ T_2 \sin \theta = T_1 \sin \theta \]

\[ T_2 = T_1 \]

(7.1)
Horizontally:

\[ T_2 \cos \theta + T_1 \cos \theta = F \]
\[ 2T_1 \cos \theta = F \]  \hspace{1cm} (7.2)

Figure 7.5: Diagram for Calculating x and y co-ordinates

\[ \tan \theta = \frac{mg}{F} \]
\[ \tan^2 \theta = \frac{m^2 g^2}{F^2} \]
\[ \sec^2 \theta = 1 + \frac{m^2 g^2}{F^2} \]
\[ \sec \theta = \sqrt{1 + \frac{m^2 g^2}{F^2}} \]
\[ \cos \theta = \frac{1}{\sqrt{1 + \frac{m^2 g^2}{F^2}}} \]
\[ = \frac{F}{\sqrt{F^2 + m^2 g^2}} \]  \hspace{1cm} (7.3)

as

\[ x = \frac{l}{2} \cos \theta \]
\[ x = \frac{l}{2} \times \frac{F}{\sqrt{F^2 + m^2 g^2}} \]  \hspace{1cm} (7.4)

\[ y = \sqrt{\left(\frac{l}{2}\right)^2 - x^2} \]
\[ = \sqrt{\frac{l^2}{4} - \frac{l^2}{4} \frac{F^2}{F^2 + m^2 g^2}} \]
\[ \theta = \tan^{-1} \frac{mg}{F} \]  
\[ x = \frac{1}{2} \times \frac{F}{\sqrt{F^2 + m^2g^2}} \]  
\[ y = \frac{lmg}{\sqrt{F^2 + m^2g^2}} \]  

7.4 Sine Curve Model

The next step was to produce a model where force was acting at more than one point, again along a string. To produce this model, a sine curve from 0 – 180° was used as the basis. At this stage, the length of the string was divided into 6 sections with the force acting perpendicular from the vertical axis. A diagram of this arrangement can be seen in figure 7.6. For each of these points where the force was acting, the tension and the angle in relation to the force was calculated. The following calculations describe the method for this at each point.
The force acting on the bottom point of the model, \textit{i.e.} where the load was hung vertically down uses the equation:

\[ mg = 2T_i \sin \theta \] (7.9)

Figure 7.7 shows the tensions acting at each segment. These points use the following equations to calculate the vertical and horizontal tensions at each point where the force was set to be acting.

**Vertical Tension:**

\[ T_i \sin \theta_i = T_{i+1} \sin \theta_{i+1} \] (7.10)
Figure 7.7: Forces Acting on a String at Each Segment

Horizontal Tension, sections 1 to 5:

\[
\begin{align*}
T_1 \cos \theta_1 &= T_2 \cos \theta_2 + \frac{F}{2} \\
T_2 \cos \theta_2 &= T_3 \cos \theta_3 + \sqrt{\frac{3}{2}} F \\
T_3 \cos \theta_3 &= T_4 \cos \theta_4 + F \\
T_4 \cos \theta_4 &= T_5 \cos \theta_5 + \sqrt{\frac{3}{2}} F \\
T_5 \cos \theta_5 &= T_6 \cos \theta_6 + \frac{F}{2}
\end{align*}
\] (7.11)

– Section 6, the top point where the muscle attached is fixed so not calculated.

\[
\begin{align*}
\frac{l}{6} \cos \theta_1 + \frac{l}{6} \cos \theta_2 + \frac{l}{6} \cos \theta_3 + \frac{l}{6} \cos \theta_4 + \frac{l}{6} \cos \theta_5 + \frac{l}{6} \cos \theta_6 &= 0 \\
\cos \theta_1 + \cos \theta_2 + \cos \theta_3 + \cos \theta_4 + \cos \theta_5 + \cos \theta_6 &= 0
\end{align*}
\] (7.12 and 7.13)

These two equations (7.12 and 7.13) represent how the net result of the curvature in
the string is zero. \(\cos \theta\) relates to the horizontal component which starts at zero, is at its maximum at the centre of the curve, and then returns to zero.

As the vertical component of the model will be equal at all 6 points, and is divided by 2 due to there being 2 strings in the model:

\[
\frac{mg}{2} = T_i \sin \theta_i
\]  

(7.14)

An Excel spreadsheet, as shown in Figure 7.8, was created to produce values for the tension and angle at each point. This involved finding values for:

\[
T_n \sin \theta_n, \quad \theta_n, \quad \cos \theta_n, \quad \sin \theta_n, \quad T_n, \quad T_n \cos \theta_n
\]

\(n = 1\) through 6

From these values, the x and y position for each point was calculated.

The input for this spreadsheet were:

- mass (\(Kg\));
- gravity (\(m/s^2\));
- length of string (\(m\));
- force (\(N\));
- \(\theta_1\).

As the value for \(\theta\) was calculated from using \(T_n \cos \theta_n\), and this was calculated using its previous value as part of the equation, there was therefore no value to use for \(\theta_1\). The
value for $\theta_1$ was selected by inputting a number, and filling out all the remaining cells using this as a basis. To see if this value used for $\theta_1$ would work, the sum of all the $\theta$ values was calculated by using Equation 7.13. The value for $\theta_1$ was manipulated until the equation result was as near to zero as possible. The remaining results would then be accurate.

The remaining results for $T_n \cos \theta_n$ were calculated as followed:

\[
\begin{align*}
T_2 \cos \theta_2 &= T_1 \cos \theta_1 - \frac{F}{2} \\
T_3 \cos \theta_3 &= T_2 \cos \theta_2 - F \sqrt{\frac{3}{2}} \\
T_4 \cos \theta_4 &= T_3 \cos \theta_3 - F \\
T_5 \cos \theta_5 &= T_4 \cos \theta_4 - F \sqrt{\frac{3}{2}} \\
T_6 \cos \theta_6 &= T_5 \cos \theta_5 - \frac{F}{2}
\end{align*}
\]  
(7.15)

The output of this spreadsheet was to find the $x$ and $y$ co-ordinates for each point. The following equations were used. The end point, where the load is attached is set to be 0,0. To find the next $y$ position:

\[
0 + \frac{l}{6} \times \sin \theta_6
\]  
(7.16)

The next $x$ position was found by:

\[
0 + \frac{l}{6} \times \cos \theta_6
\]  
(7.17)

Where 0 was the result found for the previous coordinate position. This is then repeated using the previous result to be inputted into the equation to determine the next result. This gave the coordinates for all the points, which could then be plotted onto a graph.
7.4.1 Results

The results of this model allowed graphs to be produced that graphically showed the curvature of the muscle structure with internal forces varying from 1 to 5 \( N \) and under loads of 10 and 20 \( N \). The results of these can be seen in Figure 7.9. The graphs show that as the force was increased, the displacement and the curvature increased. It can also be seen that the displacement and curvature decreased when the load was increased from 10 \( N \) to 20 \( N \). Although this model did produce graphs which visually represent the curvature of an inflating sphere, it can be seen that at each force increment, the displacement increased by an equal amount. In practice this was not the case; this model did not take into account the fact that there was a limit to the amount of contraction able to be produced, and the amount of contraction would decrease after the muscle was at near maximum inflation. This model also used force not pressure, which made it less suitable for making comparisons between the theoretical model and the actual test results.
Figure 7.8: Screenshot of Spreadsheet Produced from Sine Curve Modelling Results
Figure 7.9: Graphical Representation of a 90 mm Muscle Structure Using the Sine Curve Model Showing a 10 N (left) and a 20 N (right) Load
7.5 3-D Membrane Model

The previous method was successful at producing values which when displayed graphically, produced smooth curves. These graphs showed that as the internal force was increased, the contraction of the muscle also increased. Although this was true to reality, the values and graphs produced using this method did not take into account the way that as the internal air pressure increased in the muscle to almost full inflation, the rate of contraction of the muscle slowed. In order to allow for this, a new modelling method was developed. This method used a formula called the Runge-Kutta method as its basis, notably the fourth order Runge-Kutta formula. This method can be seen in the Appendix. Instead of having six points where the internal force acted, this method could have as many points as desired. The muscle structure was now thought of in three dimensions. The muscle structure could be sliced into annular rings and the tensions acting on each of these could be calculated to give a more accurate representation of the contraction of the muscle structure.

7.5.1 Programme Details

The model considers annular slices of the muscle as shown in Figure 7.10. The pressure on the annulus could be given by the different in the internal and external pressure multiplied by its area.

\[ F = \Delta p \times 2\pi x dz \]  

(7.18)

Figure 7.10: Representation of a Slice of the Muscle
This force acts perpendicularly to the surface of the muscle. When at equilibrium, the force would be counteracted by the curvature and tension in the annulus. Figure 7.11 shows the forces involved on the side of the annulus.

Figure 7.11: Representation of the Tension of the Muscle
The horizontal force balance gives:

\[ F \sin \theta + T_+ \cos \theta_+ - T_- \cos \theta_- = 0 \]  \hspace{1cm} (7.19)

i.e.

\[ 2\pi x \Delta p dz \sin \theta = -d(T \cos \theta) \]  \hspace{1cm} (7.20)

so

\[ \frac{d}{dz}(T \cos \theta) = -2\pi \Delta px \sin \theta \]  \hspace{1cm} (7.21)

Similarly, the vertical force balance gives:

\[ -F \cos \theta + T_+ \sin \theta_+ - T_- \sin \theta_- = 0 \]  \hspace{1cm} (7.22)

i.e.

\[ -2\pi x \Delta p dz \cos \theta = -d(T \sin \theta) \]  \hspace{1cm} (7.23)

so

\[ \frac{d}{dz}(T \sin \theta) = 2\pi \Delta px \cos \theta \]  \hspace{1cm} (7.24)

Figure 7.12: Representation of the Relationship Between \( x \) and \( \theta \)
Figure 7.12 shows the relationship between $x$ and $\theta$ on the annulus. This horizontal relationship is governed by:

$$\frac{dx}{dz} = \cos\theta \quad (7.25)$$

And the vertical equivalent states:

$$\frac{dy}{dz} = \sin\theta \quad (7.26)$$

From these it can be seen that the muscle is governed by four differential equations.

**Vertical force:**

$$\frac{d}{dz}(T\cos\theta) = -2\pi \Delta p_x \sin\theta \quad (7.27)$$

**Horizontal force:**

$$\frac{d}{dz}(T\sin\theta) = 2\pi \Delta p_x \cos\theta \quad (7.28)$$

**Horizontal position:**

$$\frac{dx}{dz} = \cos\theta \quad (7.29)$$

**Vertical position:**

$$\frac{dy}{dz} = \sin\theta \quad (7.30)$$

On expansion of equations 7.27 and 7.28:

$$\cos\theta \frac{dT}{dz} - T\sin\theta \frac{d\theta}{dz} = -2\pi \Delta p_x \sin\theta \quad (7.31)$$

$$\sin\theta \frac{dT}{dz} - T\cos\theta \frac{d\theta}{dz} = 2\pi \Delta p_x \cos\theta \quad (7.32)$$
Taking \( \cos \theta \) \( (7.31) \) + \( \sin \theta \) \( (7.32) \)
\[
\frac{dT}{dz} = 0 \quad (7.33)
\]

Taking \( \cos \theta \) \( (7.32) \) - \( \sin \theta \) \( (7.31) \)
\[
T \frac{d\theta}{dz} = 2\pi \Delta p x \quad (7.34)
\]
\[
\frac{d\theta}{dz} = 2\pi \Delta p \frac{x}{T} \quad (7.35)
\]

From this the system of four differential equations becomes:
\[
\frac{dT}{dz} = 0 \\
\frac{d\theta}{dz} = 2\pi \Delta p \frac{x}{T} \\
\frac{dx}{dz} = \cos \theta \\
\frac{dy}{dz} = \sin \theta \quad (7.36)
\]

There are four conditions. These are:
\begin{align*}
z &= 0 \quad x = 0 \quad \text{Point at bottom of muscle} \\
z &= 0 \quad y = 0 \quad \text{Point at bottom of muscle} \\
z &= L \quad x = 0 \quad \text{Point at top of muscle} \\
z &= 0 \quad T \sin \theta = mg \quad \text{Force balance}
\end{align*}

7.5.2 Programme input and output

The modelling programme created, requires a user to input certain values. These are:

- length of the muscle;
- load to be lifted;
- acceleration due to gravity (9.81 \( m/s^2 \));
- starting pressure in pascals;
- number of pressure steps;
• pressure increase per step in pascals.

The programme then used these values to calculate the curvature of the muscle at each pressure step. The final results could then be exported into a programme such as Excel to create graphs. The programme output contained the following values:

• position along the length of the muscle;
• tension along the length of the muscle;
• angle at the bottom;
• \( x \) position;
• \( y \) position.

7.5.3 Modelling Results

Figures 7.13 to 7.17 show the types of graphical results produced from the modelling programme. They represent a cross sectional view of the muscle sliced through the vertical axis. These graphs show how the curvature of the muscle rapidly increases, then the rate and amount of contraction slows as the pressure increases and the muscle structure reaches capacity. In comparison between the graphs, it can be seen that as shown in actual testing, the maximum contraction reduces as the load was increased. This can be seen most readily when comparing Figures 7.13 and 7.17, which show the contraction when lifting 10 \( N \) and 50 \( N \) loads. The muscle when lifting 50 \( N \), had a much slower rate of contraction. It required higher pressures to inflate the structure and contraction did not begin until a pressure of 0.14 \( bar \) was used. Even at the highest pressure, 0.34 \( bar \), it did not inflate fully like the results when lifting the 10 \( N \) load (Figure 7.13). The graphs show that at 0.34 \( bar \) the inflation, which was represented as the distance along the \( x \) axis, is 29.7 mm when lifting a load of 10 \( N \) and only 25.8 mm with a load of 50 \( N \). It can also be seen that the contraction was lower, as the position that the curve touches the \( y \) axis for the second time was higher than in Figure 7.13. At 0.34 \( bar \) it can be seen that the final position of the curve on the \( y \) axis with a 10 \( N \) load was 40.9 mm and when lifting a load of 50 \( N \) the \( y \) position was 54.3 mm.
It can be seen Figures 7.13 to 7.17 that as the loads were increased; the initial pressure, which caused contraction to begin, increased as the load was increased. When a load of 10 N is used, contraction begins with a pressure of 0.034 bar; the lowest pressure used. With a load of 22 N, a pressure of 0.074 bar was required, and this starting pressure increased continually up to the 50 N load requiring a pressure of 0.134 bar to begin contraction.

These patterns shown here are reflective of the actual testing results, as shown in Figure 7.18 which shows a cross sectional view of the inflated muscle structure. Here the curves produced at 0.34 bar are shown up to a load of 50 N.

Figure 7.19 compares the displacement at 0.34 bar of the actual and modelled muscle structure. It can be seen from this graph that the results of the theoretical modelling produce a smooth line; as the load increases, the amount of displacement along the $y$ axis decreases. There is a slight curve to it, which represents the slower rate of displacement as the load increases. In comparison to the theoretical model, the actual displacement produced by the muscle structure produced a lower amount of displacement. It shows the same trend of displacement reducing as load increases, but this was over a smaller range; the displacement ranges from 26.3 mm at 2.5 N load to 20.3 mm at 50 N load. In comparison, the theoretical model has a displacement range from 41.2 mm to 25.7 mm over 5 to 50 N loads. The largest displacement difference is shown at the lower loads. When lifting a load of 5 N, the largest difference in displacement was shown. This is a 15.8 mm difference. The difference in displacement reduced as the load was increased. When lifting a load of 50 N, the difference is only 5.4 mm. Compared to the theoretical model, which produced a smooth line on the graph; the actual results produced a gently undulating line. This just shows that the actual results are slightly less uniform.

There are several factors that can be taken into account to try and explain the fact that the modelled results produce greater displacement. The factor that helps explain why the actual displacement was much lower in comparison to the modelled results at low loads is the fact that the muscle structure was not fully extended to 90.0 mm. The low loads are not able to overcome the stiffness of the fabric to extend the muscle structure like the higher loads can. This caused an instant loss in potential displacement. The length of the muscle structure under various loads at 0 bar was measured. The results are shown in Table 7.1.
Figure 7.13: Modelling Result Graphically Showing the Curvature and Displacement of the Muscle as Pressure Increases with a 10 N Load at Pressures from 0.034 to 0.34 bar
Figure 7.14: Modelling Result Graphically Showing the Curvature and Displacement of the Muscle as Pressure Increases with a 22 N Load at Pressures from 0.034 to 0.34 bar
Figure 7.15: Modelling Result Graphically Showing the Curvature and Displacement of the Muscle as Pressure Increases with a 31.1 N Load at Pressures from 0.034 to 0.34 $bar$
Figure 7.16: Modelling Result Graphically Showing the Curvature and Displacement of the Muscle as Pressure Increases with a 40.8 $N$ Load at Pressures from 0.034 to 0.34 $bar$. 
Figure 7.17: Modelling Result Graphically Showing the Curvature and Displacement of the Muscle as Pressure Increases with a 50 N Load at Pressures from 0.034 to 0.34 bar
Although the length of the muscle structure is 90.0 mm, the table shows lengths of up to 97.0 mm. These lengths can be ignored, as it was a measurement taken between two fixed points, the difference in length is the focus of interest. It can be seen that the loads after 31.1 N all have a length of 97.0 mm. This is the maximum length of the muscle. This is when the load was able to overcome the stiffness of the fabric and the internal air pressure. The length of the muscle at lower loads was then subtracted from the maximum length of 97.0 mm to find the difference. It can be seen that the maximum difference is when there is no load on the muscle. Here it had a length of 91.0 mm, so therefore a difference of 6.0 mm. As expected, when the load increased, so too does the length of the muscle as the stiffness and internal air pressure can both be overcome.

During testing, this difference in starting lengths of the muscle structure was not taken into account. To see how these differences affected the displacement gap between the actual
the theoretical, the difference in muscle lengths were added to the actual displacement results. The results of this can be seen in Figure 7.19. It can be seen that it makes a small difference and raises the total displacement. It also helps to explain the large difference in displacement between the actual and theory results at low loads, as the theoretical model always assumes that the muscle is at maximum length at the start; i.e. 90.0 mm at 0.0 bar, which in practice has been found not to be the case. Another explanation for the lower displacement values is that the theoretical model does not take into account the wall thickness of the muscle structure and it assumes that it is infinitely flexible.

Figures 7.20 to 7.25 compare the displacement of the actual and modelled muscle structures with increasing pressure from 0.0 to 0.34 bar. They show the difference between a 10 N load up to a 50 N load. It can be seen again in these Figures how the theoretical model has greater displacement than the actual muscle structure. It also shows how the theory and the actual results produce the same shaped curve. As explained previously in Chapter 5, when lifting the lower loads, 10 and 15 N, the actual results produces a bi-linear curve, with a steep gradient at low pressures, showing high displacement, and a lesser gradient at higher pressures, showing less displacement due to the near full inflation of the muscle.
Table 7.1: Length of Muscle Structure Under Different Loads

<table>
<thead>
<tr>
<th>Load (N)</th>
<th>Muscle Length (mm)</th>
<th>Difference from Maximum (mm)</th>
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</thead>
<tbody>
<tr>
<td>0.0</td>
<td>91.0</td>
<td>6.0</td>
</tr>
<tr>
<td>1.25</td>
<td>92.0</td>
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</tr>
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<td>2.5</td>
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<td>3.75</td>
<td>93.5</td>
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<td>95.0</td>
<td>2.0</td>
</tr>
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<td>7.5</td>
<td>95.0</td>
<td>2.0</td>
</tr>
<tr>
<td>10.0</td>
<td>95.5</td>
<td>1.5</td>
</tr>
<tr>
<td>12.5</td>
<td>95.5</td>
<td>1.5</td>
</tr>
<tr>
<td>15.0</td>
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<td>17.5</td>
<td>96.0</td>
<td>1.0</td>
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<td>97.0</td>
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</tr>
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<td>40.8</td>
<td>97.0</td>
<td>0.0</td>
</tr>
<tr>
<td>50.0</td>
<td>97.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

structure. This bi-linear shape was mirrored in the theoretical results, but with a higher quantity of displacement. As the load was increased to 22 N, Figure 7.22, it can be seen the shape of the graph began to alter. The initial gradient of both the theory and actual results was reduced, showing that contraction occurred at a slower rate, and it can also be seen that the theoretical model did not start to produce contraction until a pressure of 0.054 bar was introduced. As with the lower loads, after a high initial rate of contraction, the rate slowed down as the muscle reaches near full inflation. Also included in these graphs is the actual displacement with the muscle starting length difference included. It can be seen that it raises the total displacement by 1.5 mm in the 10 N graph, and by 1.0 mm in the 15 and 22 N graphs. This made a slight adjustment to reduce the difference in contraction between the theory and actual results.

When the load was increased to 31.07 through to 50 N, as shown in Figure 7.23 to Figure 7.25, the shape of the graph changed slightly once again, as also explained earlier in Chapter 5. The actual results form a gently sloped s shape. This shows that at low pressures, there was little displacement. The majority of the displacement occurred between 0.07 and 0.14 bar when lifting the 31.07 N load, and 0.14 and 0.275 bar when lifting 40.8 and 50 N. After these points, the displacement then started to level out.

The theoretical models produced a similar shaped graph. As expected, as the load in-
creased, the amount of pressure required to start the contraction of the muscle increased. Loads of 31.07 N and 40.8 N required a pressure of 0.096 bar to begin the contraction and with a load of 50 N no displacement occurred until 0.131 bar. After this point, displacement occurred more rapidly than the actual muscle structure.

<table>
<thead>
<tr>
<th>Load N</th>
<th>10 N</th>
<th>15 N</th>
<th>22 N</th>
<th>31.07 N</th>
<th>40.8 N</th>
<th>50 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory (mm)</td>
<td>39.1</td>
<td>37.4</td>
<td>34.4</td>
<td>31.7</td>
<td>27.8</td>
<td>25.0</td>
</tr>
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<td>7.7</td>
<td>9.0</td>
<td>7.5</td>
<td>4.7</td>
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</tbody>
</table>

Table 7.2: Total Contraction of Theoretical Model and Actual Muscle Structure at 0.34 bar

Table 7.2 shows the amount of contraction at 0.34 bar of all of the different loads tested. It compares the theory with the actual results and from these, the difference is shown. It can be seen that at the lower loads, the difference between the theoretical and actual values is quite large. As the load increased, this difference was reduced, with only a 4.7 mm difference between the two sources. The only result that did not quite fit into this pattern was the result for the 22 N load, which had a high actual result. It can also be seen that the total difference in contraction from 10 N to 50 N was much higher in the theoretical modelling than the actual testing. The theoretical model had a displacement of 39.1 mm at 10 N and 25.0 mm at 50 N, a range of 14.1 mm. The actual results show that although the overall displacement was lower, the range was also considerably lower. At 10 N the displacement was 26.8 mm and at 50 N the displacement was 20.3 mm, a range of 6.5 mm. It would be expected that the range of the theoretical displacement would be greater due to the high levels of contraction at lower loads. This trend shows evidence that as the load is increased, the actual and theoretical results would become more similar.
Figure 7.20: Modelling Result Graphically Comparing Actual and Theoretical Displacement of the 90 mm Muscle Designs at Various Pressures with a 10 N Load

Figure 7.21: Modelling Result Graphically Comparing Actual and Theoretical Displacement of the 90 mm Muscle Designs at Various Pressures with a 15 N Load
Figure 7.22: Modelling Result Graphically Comparing Actual and Theoretical Displacement of the 90 mm Muscle Designs at Various Pressures with a 22 N Load

Figure 7.23: Modelling Result Graphically Comparing Actual and Theoretical Displacement of the 90 mm Muscle Designs at Various Pressures with a 31.1 N Load
Figure 7.24: Modelling Result Graphically Comparing Actual and Theoretical Displacement of the 90 mm Muscle Designs at Various Pressures with a 40.8 N Load

Figure 7.25: Modelling Result Graphically Comparing Actual and Theoretical Displacement of the 90 mm Muscle Designs at Various Pressures with a 50 N Load
7.6 Conclusion

This chapter has described several methods of calculating the contraction of the pneumatic artificial muscle, with each method becoming more accurate. The early methods calculated the contraction of a single force acting on a piece of string. This produced a working model, but as the pressurised air inside the muscle did not act only in one point, the model was improved upon to become more accurate and realistic with the internal air acting in multiple points. The next step saw a sine curve as its basis. This created a model, which had force acting in six points along the length of the string. As before, this was not as it would happen in reality, but it produced results, which showed the curvature of the muscle under different loads and forces, and was a more accurate representation than the first model. This sine curve model had a limitation. The graphs showed that as the force was increased, the contraction and expansion of the muscle increased by an equal amount. In practice this was not the case. This model did not take into account the fact that there was a limit to the amount of contraction produced, and the amount of contraction decreased after the muscle was at near maximum inflation. In order to obtain a more accurate model, which would take into account pressure acting over the length of the muscle structure and not just a few points, and also show how contraction slowed as the muscle became fully inflated; a model based on the Runge-Kutta method was produced. This method allowed pressure to be used rather than force, which allowed for comparison between actual and the theoretical results. This method produced a series of graphs that were able to demonstrate that contraction occurred quickly during the early stages of inflation, but slowed rapidly as the muscle reached full inflation. The graphs also showed how as the load increased, the contraction decreased, and the pressure required to start the contraction increased. This all mirrored what the actual testing of the muscle structures showed.

It can be seen from this chapter that the theoretical model assumes the muscle structure produces higher levels of displacement than the actual muscle structure is currently capable of. This has been explained by the following factors:

- the model does not take into account the wall thickness;
- the model assumes the fabric to be infinitely flexible;
• the model assumes muscle structure to be fully extended at 0.0 bar under all loads.

Although the theoretical displacement was higher than the actual displacement, it can be seen that the displacement characteristics are very similar. They follow very similar gradients and trends, showing that the theoretical model predicts the rate of contraction reasonably well. The results show that as the load increased, the accuracy of the theoretical model increased. Figure 7.25, which illustrates the actual and theoretical results with a load of 50 N, shows a similar rate of contraction and a similar final displacement at 0.34 bar. Evidence for the accuracy of the theoretical model increasing as the load was increased was shown in table 7.2, which illustrates that the difference in contraction was reduced as the load increases. If higher loads were tested it would be expected to see that the difference between the theoretical and actual results would become closer.

This model could be improved by incorporating information on the flexibility of the fabric. This would help reduce the level of contraction as the rubber coated fabric used currently is quite stiff and has limited flexibility. The model does not take this into account and so assumes the fabric to be infinitely flexible. In practice the muscle structure’s stiff fabric causes resistance against inflation at low pressures. This can be seen by the slower rate of contraction in practice than in theory as shown in Figures 7.20 to 7.25.

It can be seen in Figure 7.18 that at low loads, 5 N to 15 N in particular that the curve produced by the model is not an exact sphere. The graph shows an oblate spheroid as the shape of the muscle structure. An oblate spheroid has a y axis shorter than its x axis. This creates a squashed sphere effect. This shows that the model has inflated the muscle structure to a greater extent than it is possible to achieve. This explains why the theoretical displacements at low loads are so much higher than the actual results. At higher loads, the theoretical model produces curves, which create a prolate sphere, so the y axis is greater than the x axis. This is reflective of the actual results, showing again that the accuracy of the model increases as load increases. If the theoretical model could be improved so the curvature of the modelled muscle did not exceed $y = \frac{1}{2} x$, the curve produced would never extend past semi-circular.

Further applications of this model can be used to show the contraction of other sized muscle structures and at other loads. It could predict the muscles load capacity, how much
air pressure will be required to lift a chosen load, and the rate of contraction to be expected. These results could help in optimising other muscle designs.
Chapter 8

Muscle Suit Construction

The muscle structures designed and developed over this project were incorporated into a wearable garment. The purpose of this garment, or muscle suit, was to augment the movement of the wearer’s arm, either to reduce fatigue, to help with rehabilitation, or to aid movement for those with muscular deficiencies or paralysis. This chapter discusses the design and development of previous muscle suit arrangements, the development of the muscle suit for this project, and discusses the results. A comparison to existing muscle suits can then be drawn.

8.1 Existing Framed Orthotics, Prosthetics and Muscle Suits

Traditional prosthetic / orthotic braces use polyethylene moulded to the shape of the wearer’s body and joined laterally by Velcro. Metal beams are often used on certain body parts to prevent rotation at the attachment point and to increase rigidity [28]. These frames are then actuated by means of cables and motors. This type of prosthetic or orthotic is never incorporated in a garment. Work by Kobayashi has ruled out the possibility of attaching pneumatic muscles directly onto a fabric garment. The main concern was the stresses put onto the wearer’s bones. As the artificial muscles are mounted on top of the wearer’s own body, the bones and joints are forced to withstand the load produced by the artificial muscles. Another concern was slippage and slack. The muscles were not firmly enough attached in place to prevent the muscles from displacing when the muscles were inflated and so a
reduction in muscle stroke occurred and limited the range of motion. To reduce slippage and slack a tighter fit was required, but it was thought that this could cause difficulty when dressing [41].

To overcome these problems, a more structured or “armoured” suit was produced. A stiff cylindrical frame was developed for each upper body part. This can be seen in Figure 8.1 and consists of a $5\text{mm}$ urethane board and fabric but no metal. This armour suit was light and able to retain its shape [44].

![Figure 8.1: Soft Muscle Suit](image)

It is unclear why, but a completely hard framed suit superseded this type of suit. This armour suit used a chloroethene frame, connected by mechanical joints. This suit allows the wearer to gain the full seven degrees of freedom necessary for all seven motions produced by the arm. The total weight of the suit was quoted as $3\text{ Kg}$ in a 2005 paper [43] and as $4.5\text{ Kg}$ in a 2006 paper [40]. Both papers stated that the weight would be reduced by $1.5\text{ Kg}$ if fibre reinforced plastic was used instead of chloroethene [43]. This muscle suit has gone through many developments and the most recent design can be seen in Figure 8.2. This is a design from 2007 and shows the skeleton frame of the muscle suit. The numbers represent the McKibben muscles required to obtain all seven arm motions. One of the developments this suit has gone through can be seen in Figure 8.3. This shows how previously the cylinder used to encase the upper arm has been cut lengthwise to allow easy dressing. Dressing time
for this suit was found to be less than 30 seconds [40].

An earlier paper from 2005 describes the suit as being made up of 11 parts, one “u” section which forms the neck and shoulder structure, and two of each of the other sections shown in Figure 8.4. The sections are joined using metal connectors [43].

![Figure 8.2: Structure of Kobayashi’s Muscle Suit](image1)

The full range of motions can be seen in Figure 8.5.
Figure 8.4: New Structure of Kobayashi Frame
[43]
Figure 8.5: Range of Motions Achieved

[41]
It can be seen from the current status of muscle suits as described above and in Chapter 3 that muscle suits available or in development are bulky and cumbersome. Therefore there was a need for a muscle suit to be developed that was reduced in size and weight, but still capable of augmenting the motion of the wearer's arm. As the muscle suit produced in this project was textile based, the weight and bulk would be reduced, and the comfort level should increase, as it is a soft flexible garment. The muscle suit developed also differs from current suits with the exception from the required frame, which is discussed later in this chapter, as the rest of the suit and the muscle actuators were all made from textiles.

8.2 Muscle Suit Design in this Project

The muscle suit comprised three components: the frame to attach the muscles to, the harness to attach the frame to the body, and the jacket to disguise the frame and harness. A list of requirements that the muscle suit developed in this project must fulfill was produced. The muscle suit had to conform to the following criteria:

- not restrict the movement of users;
- lightweight;
- soft and flexible;
- suitable for daily living;
- easy to dress;
- actuators disguised by garment;
- create a reasonable amount of contraction and force.

The muscle suit created was fitted onto a mannequin. This mannequin can be seen in Figure 8.6. The mannequin was an altered polystyrene bust. A hinged arm was added to the mannequin to allow the contraction of the muscle suit to be measured. The arm was produced from a plastic tube with a hinged joint at the elbow. 10 cm of the top half of the plastic tubes were cut away at the elbow joint to allow the elbow to have the full range of contraction. This removal of the sections of tubing meant that the upper and lower arm sections could produce the same bending motion as a human arm. The arm movement was
restricted so as not to extend backwards just like a human arm. The arm was created in accordance with anthropometric data to the average length of a female arm. It was then connected to the mannequin on a metal rod inserted through the width of the mannequin at the shoulder joint height.

8.2.1 Harness Design

The pneumatic muscle structures, which actuate the muscle suit, need to be attached in a suitable manner to the garment. This method of attachment must hold the muscle structures securely in place, accommodate and distribute the forces created by the contraction and relaxation of the muscle structures, be comfortable to wear and not impede normal motion of the wearer. Unlike the suit made by Kobayashi and his team, a full body frame is not desirable as this would add bulk and create an unattractive garment. It is also not necessary for the range of movement that is required in this project, as the aim of this project
is to give some support to daily movement. In order to find a suitable solution, harness patterns for prosthetic arms were studied. The harness refers to the method of attaching the prosthesis to the wearer. There are several different types of harness for prosthetic arms. For these users, the harness is chosen by the level of arm amputation and their strength requirements [35]. To meet the needs of the harness required for this muscle suit, harness patterns for transhumeral amputation were studied. This type of amputation refers to any amputation occurring above the elbow. These harnesses are most suitable for use in this project, as the muscle structures used need to be anchored at the shoulder just like upper arm prostheses.

Figure 8.7 shows the two types of transhumeral harnesses. According to Pursley (1955), “from the wearer’s point of view, the above-elbow figure-of-eight harness constitutes the easiest way of meeting the requirements of the above-elbow case”. The basic structure of the figure-of-eight harnesses uses a loop around the opposite shoulder; the front part of the harness providing support to the arm and the rear would attach to the cable controlling flexion of the prosthesis and also help to distribute the load [63]. This type of harness is suitable for light to normal activities, and its advantages are that it is simple, durable and adjustable. The disadvantage of this design is that pressure on the opposite shoulder can cause discomfort [35]. The second harness shown in Figure 8.7 is the Shoulder Saddle and Chest Strap harness. This harness is employed if the user is involved in heavy duty work. The shoulder saddle reduces the stress on the shoulder and the chest strap harness provides greater comfort. These improvements in comfort allow greater loads to be accommodated [63]. Although this design has the advantage over the figure-of-eight harness of having greater comfort and lifting abilities, it has the disadvantage of having reduced control, and is difficult to wear and adjust in women because the straps cross the breasts [35].

Considering the advantages and disadvantages of the harnesses described above, the figure-of-eight harness was chosen to be incorporated into the muscle suit. This will allow easy access to the garment, is suitable for male and female users and for the type of lifting that the muscle suit is aimed at, namely light to normal lifting activities is sufficient. As described in The Gale Encyclopedia of Nursing and Allied Health, the harnesses are usually made using polyester Dacron straps [45]. This material is used as it has high tensile strength, very low stretch, and has good abrasion resistance [1]. A generic form of this strapping was
used to produce the harness. The harness can be seen in Figure 8.8.

It can be seen in Figure 8.9 that the harness is not a straightforward figure-of-eight harness. Some alterations have been made to help spread the load created by the force of the muscles contracting. Strap A was added to help spread the load over both sides of the upper body. Strap B was added to help prevent the frame from being pulled forwards as the muscles contract.
8.2 Muscle Suit Design in this Project

Figure 8.8: Figure-of-Eight Harness on Female Mannequin

Figure 8.9: Figure-of-Eight Harness Showing Additional Strap Detail
8.2.2 Frame Design

As previously discussed in this chapter, the bones of the arm alone are not sufficient to act as a frame for the muscle structures. The inflation of the muscle structures would put too much pressure on the bones and joints and cause strain and discomfort to the wearer. This chapter also discussed the phenomenon described by Kobayashi of slippage and slack created in the muscle structures when attached directly to a garment [41]. Due to these factors a frame had to be incorporated into the garment. It is not ideal to have a frame as it increases the weight and possibly reduces comfort. It also prevents the garment from being soft and flexible and may reduce the overall aesthetic quality of the garment. Despite this, it is necessary for the factors mentioned before, so it was designed to be as minimal and lightweight as possible.

![Deconstructed Frame](image)

Figure 8.10: Deconstructed Frame

The frame was manufactured using aluminium and can be seen in Figures 8.10, 8.11 and 8.12. Aluminium bars with a cross section of 15 x 2 mm were used. This allowed the frame to be lightweight, strong and resistant to torsion. Figure 8.10 shows the deconstructed frame with each section labeled. It can be seen from this figure that the frame consisted of five sections of the aluminium sheeting joined at the elbow, which was freely moveable. The frame for the lower arm consisted of two sections, A and C, which were of equal size. These ran from the wrist to the elbow. The upper arm from the elbow to the shoulder also consisted of two sections, B and D, which were of different sizes and designs. Section D ran from the outer shoulder to the elbow and section B curved round the inner part of the shoulder to
the under arm and then ran straight to the elbow. Sections A and B were bolted together, as were sections C and D, and D to F. An earlier design had section B finishing under the armpit, where it would attach to the harness. After initial testing it was made clear that this design was not a functional choice as the strain caused by the contracting muscle structures resulted in the metal frame digging uncomfortably into the armpit. With this piece of frame removed, and just the outer arm section, section D, for support, the frame was flexing under the strain of the contraction. The strain was needed to be shared onto a second upper arm piece of frame. To overcome the problem of how to attach the inner upper arm section, section B, to the shoulder section, section F, a design that curved over the contours of the shoulder was produced. Section B could then be attached by a bolt to section F, which rested on the shoulder and was an \( L \)-shaped section. This produced a more solid frame and allowed the strain produced by the muscles to be more evenly distributed throughout the frame, and also distributed through the harness. To allow the metal of the frame to lie flat against the shoulder and the inner arm, a 90° twist was added to the aluminum at the under arm point in section B. The frame was attached to the harness via section F. This fitted of the top of the shoulder and then was attached to the harness by inserting into a tight pocket. This is illustrated in Figure 8.9 as strap C.

The elbow joint also included a semicircular piece of aluminium, section E, which fitted over the elbow. This acted as a join between the aluminium sections on the inner and outer arm, and also as the anchor point for the string of muscle structures to increase the contraction as described in Chapter 6.9. The joins of sections A and B, and C and D had section E added. The join was left loose to allow the flexibility of the elbow joint not to impede the contraction of the actuators.

To attach the string of muscle structures to the frame, holes were drilled on either side of the frame at the wrist point on sections A and C, and another two holes were drilled in section F, at the top of the shoulder. The strings of muscle structures could then be attached to the frame, passing under semicircular section E at the elbow. To avoid using the sleeve of the garment alone to raise the lower arm under inflation of the muscle structures, a piece of fabric was attached to the sections A and C at the wrist. This can be seen in Figures 8.11 and 8.12. The fabric was attached to the frame by sewing channels down the length of the fabric then sliding the fabric onto the frame. Under inflation of the muscle structures, this
acted like a sling to raise the arm. As the fabric created a large contact surface onto the arm, it would also spread any load acting on the lower arm. Figure 8.13 shows the strings of muscle structures in a relaxed state, attached to the frame. The total weight of the frame was 0.154 Kg.

Figure 8.11: Annotated Muscle Suit Frame

Figure 8.12: Side View of the Muscle Suit Frame
Figure 8.13: Annotated Diagram of Mannequin with Harness, Frame and Muscle Strings Attached
8.3 Muscle Suit Jacket

The muscle suit was constructed from two ready-made jersey zip up jackets. These were then altered to incorporate the harness and frame for the attachment of the muscle structures. The first stage of construction was to create the harness. The harness was produced using the same polyester strapping as described in Chapter 8.2.1. The design used was again a figure-of-eight design, but it can be seen in Figure 8.15 that the design differed slightly from the initial design shown in Figure 8.8. During testing it was decided that the additional strap (strap B in Figure 8.9), which was designed to reduce the forward pull from the contraction of the muscle structures, could be improved upon. It can be seen in Figure 8.14 that the tight pocket that the aluminium frame is inserted into (strap C in Figure 8.9) had been lengthened to allow improved stability for the attachment point of the frame into the harness. It can also be seen on this figure how the curved shoulder piece of the frame (section C), attaches to the harness via a bolt which goes through the harness and the frame. This created a firm joint between the frame and jacket. In addition to the lengthened pocket, two additional straps were attached to this and to the back strap of the harness, which can be seen in Figure 8.15. The overall result of this was to improve the stability of the harness and reduce the pull on a localised area by helping to spread the load across the back. The harness was sewn on to the back of the jacket, but the straps going around the front of the shoulders were left unattached to allow the placement of the straps to be determined by the wearer to improve the comfort of the harness. The use of a jacket to line the muscle suit would also improve the comfort as the frame and harness would not be in direct contact with the wearer’s skin.

The second stage in production was to cover the harness and frame to create a more aesthetically pleasing garment. The final design of the muscle suit jacket can be seen in Figure 8.16. For this a second jacket was used. This outer jacket was linked to the lining jacket by sewing the seams sleeve without the frame together, removing one of the zips and sewing the jacket down the front of the garment and also by removing one of the hoods and sewing the jackets together along the length of the neckline. The sleeve on the outer jacket, which would cover the frame, was unstitched along its seam and as the sleeve was too narrow to cover the frame, an additional panel of fabric was sewn into the sleeve. To allow easy access to the frame and muscle structures an open ended zip was sewn up the
seam of the sleeve. This can be seen in Figure 8.17. This allowed access for removal of the frame and muscle structures to allow for washing. The unzipped sleeve showing access to the frame can be seen in Figure 8.18. A hole was also created in the shoulder of the outer jacket to allow the silicone tubing from the muscle structures to be attached to a compressed air line. The total weight of this jacket was 0.55 $Kg$. 
Figure 8.15: Harness and Jacket Lining of Muscle Suit
Figure 8.16: Front of Muscle Suit
Figure 8.17: Back of Muscle Suit
Figure 8.18: Muscle Suit Showing Unzipped Sleeve with Frame Accessible
8.4 Summary

It has been shown in this chapter that PAMs have been successfully incorporated into a wearable garment. The garment chosen for this was a zip up sweater jacket. This garment was a good choice as the figure-of-eight harness could be incorporated easily. This zip up design allowed for easy dressing and although the jacket created in this project is of female design, can be a unisex garment. When the jacket is worn, it is noticeable that it is not a normal jacket, but it is not obvious why. The jacket disguises well what is underneath. Except for the tubes for the compressed air, there are no visible parts of the harness, frame or muscle structures. This would be pleasing to a wearer who wanted the use of the jacket to be less obvious. It is an aesthetically pleasing garment as it uses a jacket design that is commonly worn so again it is less obvious that there is anything special about the jacket. In comparison to other muscle suits used for augmenting the wearer’s arm, as discussed in Chapter 3, this jacket is more flexible, soft and lightweight due to being textile based and a more traditional garment. The total weight of the jacket including the frame and the muscle structures was 1.2 $Kg$. The most notable contributor to this weight was the weight of the valves. The ten valves used in the six muscle structures was 0.285 $Kg$, whereas the actual muscle structures only weighed in at 0.086 $Kg$. Although a lighter valve was trialled earlier in the development stages which weighed half the weight, the elbow joint of this heavier valve made for a neater connection between the muscle structures as the tubing would run parallel to the wearer’s arm. The next chapter investigates how well the muscles suit performs in a number of tests. The load vs. contraction is tested, along with the speed of contraction and fatigue testing.
Chapter 9

Testing of the Muscle Suit

In order to fully evaluate the muscle suit’s capabilities, a range of tests were carried out. An angular contraction test was carried out. This showed the contraction created by the muscle suit when various loads were attached at the hand position of the mannequin and with various pressures. These results could then be compared to the contraction created when using the muscle structures with a rig, as described in Section 6.10. The second test measured the contraction reaction time when at 0.35 and 0.7 bar with various loads attached at the hand position. The final test was to evaluate wearer fatigue. This would show if the muscle suit could help with muscle strength performance, repetition and reduce fatigue.

9.1 Angular Contraction Testing

The angular contraction of the muscle suit was tested. This evaluated the performance of the muscle structures when in-situ in the muscle suit. The mannequin was used rather than a human for this stage of testing. The harness and frame were attached to the mannequin, and weights were attached at the location of the hand. These weights complemented the weight of the arm itself. The angle at the elbow was recorded at 0.07 bar intervals, from 0 - 0.7 bar and then back to 0 bar. The test was repeated four times and an average taken. The testing set up can be seen in Figures 9.1 and 9.2. From these pictures it can be seen that when the arm is relaxed, it does not hang completely vertically. This is due to the tension from the string of muscle structures. If the arm were allowed to hang completely vertically, too little contraction would be produced, as the muscle structures would waste contraction on removing the slack and creating tension along the string of the muscle structures. If the
initial tension is low, the contraction created from the muscle structures is not wasted. The arm in a relaxed state would hang vertically downwards at an angle between 40 - 50°. The results in the following section show the overall change in angle created, i.e the total change in angle from 0 bar to 0.7 bar.

Figure 9.1: Testing Set-Up of Muscle Suit with Muscle Structures Uninflated
Figure 9.2: Testing Set-Up of Muscle Suit with Muscle Structures Inflated
9.1.1 Results and Discussion

Figure 9.3 and Table 9.1 show the results of the angular contraction of the muscle suit when lifting various loads. As expected it can be seen that the contraction decreased as the loads were increased. It can be seen that when the suit was lifting no load, the maximum average displacement was 61.5°. This was naturally the highest level of contraction produced during this test. Although there was no load attached to the hand position of the mannequin, the weight of the arm and the muscle suit still needed to be lifted. The arm weighed 0.208 Kg and the frame and muscle structures weighed 0.36 Kg. The majority of this weight was made up from the ten valves on the muscle structures, which accounted for 0.245 Kg. It can also be seen that with no load, the angular displacement on the relaxation of the muscle structures was very slow. This may have been due to there not being enough load to overcome the stiffness of the fabric. This would reduce the speed at which the air was expelled from the muscle structures, compared to when loads were attached to the arm. The contraction remains around 60° until the pressure had dropped to 0.21 bar. This may have been due to slight stiffness of the elbow joint of the muscle suit frame, so the lack of load was unable to overcome this stiffness. It can be seen in Figure 9.1 that as the load was increased, the rate of displacement of the relaxing muscle structures also increased. As the load was increased to 5.0 N, the angular displacement was almost halved, to 36.7°. Although a decrease in contraction was to be expected, this result was not as high as expected as the decrease was less when the muscle structures were evaluated against the vertical testing carried out and described in Section 6.10. It would have been preferable for the contraction not to reduce so greatly.
### Table 9.1: Average Angular Displacement of Muscle Suit

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<td>33.7</td>
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<tr>
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<td>60.3</td>
<td>50.8</td>
<td>43.0</td>
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<td>32.0</td>
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<tr>
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<td>40.8</td>
<td>33.3</td>
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<tr>
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<td>45.3</td>
<td>37.8</td>
<td>30.3</td>
<td>27.0</td>
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<td>41.8</td>
<td>33.3</td>
<td>27.0</td>
<td>24.0</td>
</tr>
<tr>
<td>0.069</td>
<td>49.8</td>
<td>33.3</td>
<td>27.8</td>
<td>21.3</td>
<td>17.3</td>
</tr>
<tr>
<td>0</td>
<td>17.0</td>
<td>12.5</td>
<td>8.0</td>
<td>5.3</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Figure 9.3: Average Angular Displacement of Muscle Suit at Various Loads
Figure 9.4 compares the angular contraction of the vertical testing described in Section 6.10 and the mannequin testing. The graph shows the results from Section 6.10 when the muscle strings were anchored 5 cm from the pivot. This is approximately the same distance that the muscle strings in the muscle suit are anchored from the wearer’s elbow. It can be seen that the contraction produced by the mannequin is higher than that of the vertical rig testing when lifting low loads. With no load, the mannequin contraction is 4.8° higher, but as the load was increased, the contraction of the mannequin dropped at a faster rate than the vertical testing rig. This initial higher contraction can be explained by the lower weight of the mannequin arm in relation to the vertical testing rig arm. As expected the greatest difference in results is when the load was greatest, a 8.0° difference when the load was at 5.0 N. As the loads increased, other factors came into play to produce lower contraction in the mannequin. These are,

- Slack in the frame. Although the frame is kept slightly taught during relaxation, on initial inflation there was still some movement in the frame before the arm began to move.
9.2 Speed of Response Testing

The speed of contraction was also tested. This was recorded as the time taken for the muscle structures to inflate and contract the arm to their maximum ability at various loads at air pressures of 0.35 and 0.7 bar. The regulator used for testing was connected to an air supply valve, which allowed the flow of air to be constant at a set pressure. The time taken for the arm to react was recorded on a stopwatch. Although this cannot be considered a highly accurate way of measuring, as the time taken for contraction was relatively fast, it was still capable of giving a good indication of the reaction time. Along with the time, the angular contraction produced was also recorded and the angular velocity calculated. This allowed comparison between the contractions produced when the muscle structures were slowly inflated compared to when very quickly inflated. The test was repeated four times and averages taken. Again the angle at which the arm started to contract from was not 0°, but for the purpose of this test the results are shown as the total angular change in contraction.

9.2.1 Results and Discussion

It can be seen in table 9.2 that the time taken for the arm to contract decreased, as the load and pressure increased. The reduction in the time taken for the arm to contract as the load increases can be explained by the reduction in angular contraction of the arm. As the arm does not move as far, the time taken will clearly be less. As the pressure was altered from 0.35 bar to 0.7 bar the time taken to contract was reduced. The higher pressure allowed the muscle structures to inflate more fully and at a higher speed. There was also a higher initial burst of energy, which created the faster inflation. The results show, that as expected,
the angular velocity decreased as the load was increased. The angular velocity then also increased as the pressure was increased from 0.35 bar to 0.7 bar. This is shown on Figure 9.5.

It can be seen that the amount of reduction in contraction time and angular displacement as the load increases, is almost equal at 0.35 and 0.7 bar. The range in angular displacement over the tested loads at 0.35 bar falls by 20°, and the fall at 0.7 bar was 19.5°. The fall in contraction time at 0.35 bar was 0.12 seconds and at 0.7 bar was 0.13 seconds. This may indicate that the amount and time taken for contraction could be predicted. The results of this test have shown that whatever the load or pressure, that there was always a fast response of contraction. The contraction of the arm does not creep up slowly; the motion is a fast and single motion. Results from this test points to a scenario where the muscle suit could be used in rehabilitation. The muscle suit could be worn and the pressure set to a determined level to create the desired movement of the wearer’s arm to suit his / her ability. This would help to improve the muscle strength of the wearer’s arm, by gentle and regular movement possibly adjusting the level of assistance as the wearer strength improves.

<table>
<thead>
<tr>
<th>Load N</th>
<th>Angle °</th>
<th>Time (s)</th>
<th>Angular Velocity (°/s)</th>
<th>Angle °</th>
<th>Time (s)</th>
<th>Angular Velocity (°/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>47.0</td>
<td>0.50</td>
<td>94.0</td>
<td>0.35 bar</td>
<td>56.5</td>
<td>0.48</td>
</tr>
<tr>
<td>1.25</td>
<td>37.0</td>
<td>0.48</td>
<td>77.1</td>
<td>0.35 bar</td>
<td>56.0</td>
<td>0.45</td>
</tr>
<tr>
<td>2.5</td>
<td>32.3</td>
<td>0.50</td>
<td>64.5</td>
<td>0.7 bar</td>
<td>45.0</td>
<td>0.40</td>
</tr>
<tr>
<td>3.75</td>
<td>29.7</td>
<td>0.38</td>
<td>78.1</td>
<td>0.7 bar</td>
<td>40.0</td>
<td>0.35</td>
</tr>
<tr>
<td>5.0</td>
<td>27.0</td>
<td>0.38</td>
<td>71.1</td>
<td>0.7 bar</td>
<td>37.0</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Table 9.2: Average Angular Displacement, Time of Contraction and Angular Velocity of Muscle Suit

9.3 Human Fatigue Testing

The muscle suit was tested to see if it was capable of reducing human muscle fatigue. Muscle fatigue is the temporary reduction in muscle strength and power due to the prolonged contraction of the muscle. This is caused by a lack of oxygen, and an increase of blood and lactic acid in the muscle. Muscle function is not fully recovered until this build up of lactic acid has been removed and processed by the body. To see if the muscle suit could improve endurance and therefore reduce fatigue, a simple test was constructed. The test was based
on Mosso’s ergograph. This is so named after its inventor Angelo Mosso (1846-1910), an experimental physiologist from Turin, Italy. Mosso studied the effect of muscular training on fatigue and his studies demonstrated that exercise would increase muscular strength and endurance while prolonging the occurrence of fatigue. Mosso compared the fatigue in a test subject’s finger before, and after exercises to improve the muscular strength [27]. Figure 9.6 shows the ergographic tracing of muscular fatigue. It shows how after muscle training, fatigue is greatly reduced. This is shown by the rapid drop in amount of contraction in graph A which is pre-training, compared to the more sustained and high amount of contraction, which takes longer to decrease in graph C which is post-training.

This way of testing fatigue was phased out at the beginning of the 19th century. The dynanometer and ergometer became its replacement. These are still used in cardio-vascular gym equipment. These methods are used to measure strength and integrate modes of resistance, but do not necessarily produce a graphic record like that of the ergograph [2]. Because a graphical representation of how the muscle suit responds to fatigue is wanted, ergograph testing was used.

Ergograph testing has previously been discussed in Section 3.2.4 as the Wearable Power
Chapter 9: Testing of the Muscle Suit

Figure 9.6: Ergographic Tracings of Voluntary Muscle Contractions by the Middle Finger. Showing Before (A) and After (C) the Effects of Physical Training on Muscle Performance

[27]

Assist Device was tested using this method [68]. This test measured the height and number of repetitions of a biceps curl from vertical extension that the test subject could perform in 300 seconds. This time was chosen, as it was the length used by Sasakil et al (2004) in their ergograph, and this duration is long enough for fatigue to set in. The test was then repeated whilst wearing the muscle suit after a break of 24 hours, to allow the test subject to fully recover from the fatigue.

A modified version of Mosso’s ergograph set up was constructed. This used a plastic channel attached to a metal frame. The plastic channel provided a guide for the load, which was raised and lowered up and down its length. The height that the load was lifted was measured and plotted against time. This can set up can be seen in Figure 9.7. This figure shows the weight in different positions in the channel. The load chosen to be tested with was a 10 N load. The 300 second test was filmed so the maximum and minimum height that the load was raised and lowered could be accurately measured and the time taken for each stroke could be recorded. When wearing the muscle suit, the air pressure was raised and lowered between 0 and 0.7 bar. This test was to show how the muscle suit would reduce muscle fatigue, so the subjects would be using both their own muscular strength and the support of the muscle suit to lift the load. Two healthy female test subjects were used, as
the suit was designed for an average-sized woman. The test subjects were asked to perform a biceps curl in a controlled manner at a regular pace of their choosing, but to use the same pace for both parts of the tests, as shown in Figure 9.8.

Figure 9.7: Images of Fatigue Test Set-Up

9.3.1 Results and Discussion

Figures 9.9 and 9.10 show the results of the fatigue testing on two test subjects. The first test on each of the test subjects was without the muscle suit. It can be seen on these graphs that the amount of contraction able to be produced decreased as time increased. This was to be expected as this shows muscle fatigue occurring. Subject 1 was lifting the load by around 0.53 m at the start of the test, but as the test continued, contraction decreased to below 0.40 m. Subject 2 was lifting the load to a slightly lower height, with a 0.50 m lift on average, falling to an average of 0.36 m. It can also be seen that the rate of contraction slowed slightly over the duration of the test for both subjects, again a side effect of muscle
fatigue.

When the muscle suit was worn it can be seen that the amount of contraction was much more constant for both of the subjects. The test subjects were able to keep a more constant and sustained contraction of between 0.48 and 0.60 m for subject 1, and between 0.45 and 0.56 m for subject 2. No signs of muscle fatigue were shown as the level and rate of contraction did not decrease. This shows that the support that was provided by the muscle suit was enough to reduce muscle fatigue. The number of contractions were slightly less (−3%) when wearing the muscle suit in both test subjects. This was due to the time taken for an operator to open and close the compressed air supply.

From the results of the fatigue test, the total work done was calculated. The following equation was used:

\[ \text{Work done} = \text{force} \times \text{distance} \]
The force stayed constant at 10 N and the displacement of the load was taken in metres. This gave the work done in $kJ$ for each biceps curl, contraction and relaxation. The total
work done in the 300 s test was calculated and the results can be seen in Table 9.3. It can be seen that the total work done is greater when both testers were wearing the muscle suit. This is reflective of the consistency of the contraction. When wearing the suit, the contraction did not decrease as time continued. This again shows that fatigue had been reduced.

<table>
<thead>
<tr>
<th>Tester</th>
<th>Work Done kJ</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Suit</td>
<td>1.583</td>
<td>1.739</td>
</tr>
<tr>
<td>1</td>
<td>With Suit</td>
<td>1.739</td>
<td>1.739</td>
</tr>
<tr>
<td></td>
<td>No Suit</td>
<td>1.491</td>
<td>1.654</td>
</tr>
<tr>
<td>2</td>
<td>With Suit</td>
<td>1.654</td>
<td>1.654</td>
</tr>
</tbody>
</table>

Table 9.3: Total Work Done in kJ of Tester’s Biceps Curl with and without Wearing Muscle Suit
Chapter 10

Conclusion and Suggestions for Future Work

The aim of this project was to explore ways in which to create a muscle suit for augmenting the movement of the arm. The wearer may require the help of this muscle suit for a number of reasons. They could be elderly and have limited strength or mobility in their arm so requiring extra help in daily activities. They could have a muscular deficiency or injury and again require help in daily activities or help with rehabilitation. They could also be a manual worker requiring muscular fatigue reduction when carrying out repetitive actions.

This muscle suit needed to be actuated by controllable and reliable means. Options of actuating the muscle suit were investigated to find suitable options for how to solve this problem. Section 2.2 investigated the possibility of using electroactive polymers as the means of actuation. After careful consideration the use of electroactive polymers was ruled out, as one single type of electroactive polymer could not achieve all the pragmatic requirements needed from an actuator. These included fast actuation, and the ability to hold a force.

The next option for actuation was pneumatic artificial muscles (PAMs). These are a more established means of actuator in the field of orthotics. The many types of PAM were studied along with their integration into powered orthotics or muscle suits. The main type of PAM used in this area is the McKibben muscle. This is in the braided class of PAMs. Hiroshi Kobayashi had incorporated the McKibben muscle into an upper body muscle suit,
which facilitated the required movement but was large and bulky. The current project tried to combine the mobility of Kobayashis suit with a lighter and more wearable design.

After studying a range of old and new muscle suits / wearable powered orthotics, discussed in Chapter 3, it became clear that there was no muscle suit past or present, that was constructed using textile materials. For a product that is designed to be worn like clothing, it would be advantageous to create a textile-based approach. It was therefore decided to create a muscle suit that was as textile-based as practicable. This resulted in the final jacket being discrete and having the comfort of a regular textile jacket.

The outcome of this project is the development of a new muscle suit, powered by a new type of pneumatic artificial muscle. The new artificial muscle created differs from current PAMs as it is made entirely from textile materials. This has allowed the design to be lightweight and flexible. The muscle structure created would be classed as an embedded PAM due to the rubber coated cotton fabric used for the panels, and due to the Kevlar strands which run longitudinally down the length of the panel seams forming “tendon” like structures. As these are incorporated into the internal part of the muscle structure and also help restrict the inflation of the structure, this PAM would fit well into this category. This design has also shown that it can be easily made into various sizes to create different contraction properties. Testing of this PAM has shown that it has a relatively high force to weight capacity; a structure with a diameter of 90 mm, and mass of 43 g is able to easily lift loads in excess of 50 N. Linking these small structures in series increased the contraction capabilities and created a more suitable design for incorporation into the muscle suit, than using just one larger PAM.

The suit created around the muscle structures is again different to current muscle suit designs. Its textile form with incorporated aluminium frame allows the suit to have the best properties from each component. The textile jacket allows for a lightweight, flexible, traditional and aesthetically pleasing garment. The incorporated aluminium frame creates a strong but lightweight attachment point for the muscle structures, and reduces the strain placed on the wearer’s bones during contraction. The muscle suit created also differs from current muscle suits as it takes inspiration from prosthetic limb design. The way that above-elbow prosthetic arms are attached to the wearer was studied. This allowed this already well
established area of prosthetics to influence how to attach the frame and muscle structures into the garment. The figure-of-eight harness design was used and modified to create a strong and comfortable attachment to the frame. This design allowed for easy dressing, could be well incorporated into the zip up jacket design, and was suitable for male and female users. A traditional, everyday jacket was tailored around the harness and frame to create a jacket with hidden muscle suit properties for one arm muscle actuation, with a total weight of 1.2 Kg. These results show that the muscle suit has conformed to the list of requirements in Section 8.2. These were:

- not restrict users;
- lightweight;
- soft and flexible;
- suitable for daily living;
- easy to dress;
- actuators disguised by garment;
- create a reasonable amount of contraction and force.

The testing of the individual and the linked muscle structures showed good levels of contraction and load carrying performance. When the muscle structures were incorporated into the muscle suit, the lifting and angular contraction performance reduced. The reasons for this were explained in Section 9.1.1. Overall the project has reached its aims, as it has shown that low loads are able to be lifted whilst using the muscle suit, which would be suitable for light daily activities, and also that it reduces fatigue, which would be good for repetitive movements for manual workers. To allow higher loads to be lifted whilst using the muscle suit, further work would need to be done on creating a higher performing PAM.

A way of optimising the PAM created in this project could be to improve the sealing of the seams. When the muscle structure was tested to failure, the only part of the structure to fail was the seams. A small leak formed in the seam, which prevented the structure from bursting, or failing elsewhere. This showed that the silicone seam was the weakest link. If the sealant could be optimised, to create a stronger, but no less flexible join, the seal of the seam may improve. This would allow air pressures of above 0.7 bar to be used which,
would improve the contraction, especially at higher loads. Another way to overcome this problem would be to create a seamless structure. If the muscle structure could be produced in one piece and then rubber coated, the risk of seam failure would be removed, as there would be no seams in the structure. This would mean that there would be fewer weak points for air to potentially escape. The fibre and coating material could also be chosen to create a structure that was strong and inextensible, but also lightweight and flexible. The higher the flexibility of the fabric used, the lower the air pressure needed to begin inflation, and the faster the deflation at low loads. This is all due to the low rigidity in the fabric.

When compared to other PAMs, the PAM created in this project has some different qualities to those studied. Although the PAM in this project is more suitable for lifting lower loads than the McKibben, Saga or Pleated PAM, this created the advantage of being more sensitive at lower air pressures. This project’s PAM is capable of creating force at pressures as low as 0.035 bar and had been tested up to 0.7 bar. The Saga PAM requires pressures of 0.5 bar to activate contraction [9] and the pleated PAM is capable of creating force at 0.02 bar, but generally has a working range of 1-3 bar and the McKibben muscle has a working range of 1-5 bar [73].

The PAM in this project was made smaller than the PAMs studied. It was after researching Saga’s PAM which used a ring around the middle of a PAM to create two joined spherical structures which increased the contraction which influenced the direction to have smaller muscle structures linked together. A large PAM would also not be easily incorporated into a wearable garment. The smaller size has negatively affected the contraction capabilities, but it made the integration into a wearable garment more aesthetically pleasing. In comparison to the most popular PAM, the McKibben muscle, the PAM produced in this project performs comparably. Information from The Shadow Robot Company website [5] shows that a 150 mm McKibben muscle, their smallest “off the shelf” product, creates a 30 N pull at 3.5 bar and has a maximum pull of 70 N. The PAM, which was created in this project, was smaller at 90 mm and showed lifting capabilities in excess of 50 N at 0.7 bar. If this PAM was tested to higher loads, it would be expected that it would be able to lift loads comparable to the McKibben muscle.

The muscle structures were incorporated well into a wearable garment. Apart from the
air tubes, the garment produced had no part of the frame and muscle structures showing. The whole actuating part is enclosed within a double layer of fabric in the sleeve. The design of the jacket, with a zip up the centre front, allowed easy dressing and is in a unisex style. The jacket could be created to be multi sized. If the harness had a buckle incorporated, then it could be fully adjustable to fit any wearer. The frames could come in a range of sizes to incorporate different lengths of arm, and this could just be slotted into the harness on the correct sized jacket.

The most comparable muscle suit already developed would be Kobayashi’s muscle suit. This is because it has similar aims of creating a wearable upper body muscle suit, and it augments the wearer’s arm motions. It can be seen in Section 3.2.3 that Kobayashi’s muscle suit started out as a textile-based idea, but then turned into a more “armour” based suit. This suit is capable of augmenting the movement of both of the wearer’s arms with 7 degrees of freedom, the same as a human arm. The suit created in this project only set out to augment one arm, but could be easily altered to augment both. It is not able to create the same number of motions as Kobayashi’s suit. It was just concerned with raising the hand with the elbow bent. This is why it used fewer PAMs than Kobayashi’s suit. Overall Kobayashi’s suit can create more movement and lift higher loads, but it is heavier, bulkier and much less aesthetically pleasing than the suit created in this project. It can therefore be seen that the main obstacle facing research in this field is looks versus functionality. Does one create a very functional muscle suit, but sacrifice looks, wearability and comfort, or an aesthetically pleasing muscle suit with a more limited range of movement? This project has created a muscle suit, which has become weighted on the side of looks rather than functionality. Although it does have reasonable contraction and force generation, further development into a more powerful artificial muscle for incorporation into this project’s jacket, would help bridge the technology gap between function and aesthetics.
Appendix A

Runge-Kutta Method

Nomenclature:

- $x, y$: $x$ and $y$ coordinates
- $h$: Interval size
- $k$: Estimated slope
- $f$: Time derivative

The Runge-Kutta method is a method used to solve the integration of ordinary differential equations. It is an advanced method based on the Euler method, shown in equation A.1.

\[ y_{n+1} = y_n + hf(x_n, y_n) \]  

(E.1)

Euler’s method is the simplest but also the least accurate method for integrating ordinary differential equations. The derivative at the starting point of each interval is extrapolated to find the next function value as seen in Figure A.1. Euler’s method is not recommended for practical use as it is not very accurate when compared to other methods and it is also not very stable. Euler’s method has first order accuracy.

To improve the accuracy, a “trial” step can be taken to the midpoint of the interval and then from this the value of $x$ and $y$ at the midpoint can be used to calculate the “real” step for the whole interval. This can be seen in Figure A.2. This method has increased accuracy and can be called the midpoint method, or the second order Runge-Kutta method and the
Figure A.1: Euler’s Method

The equations for this method can be seen in equation A.2.

\[ k_1 = hf(x_n, y_n) \]
\[ k_2 = hf(x_n + \frac{1}{2} h, y_n + \frac{1}{2} k_1) \]
\[ y_{n+1} = y_n + k_2 + O(h^3) \] (A.2)

Figure A.2: Midpoint Method

[62]
This method can be further evaluated to create different coefficients of higher order error terms. The order used in this modelling is of the forth order shown by equation A.3. This method takes four evaluations of the derivatives for each step, once from the initial point, twice at the trial midpoints and once at the trial endpoint, which can be seen in Figure A.3. From these derivatives, the final function value can be calculated. This method is more accurate than the midpoint method [62].

\[
k_1 = hf(x_n, y_n)
\]
\[
k_2 = hf(x_n + \frac{h}{2}, y_n + \frac{k_1}{2})
\]
\[
k_3 = hf(x_n + \frac{h}{2}, y_n + \frac{k_2}{2})
\]
\[
k_4 = hf(x_n + h, y_n + k_3)
\]
\[
y_{n+1} = y_n + \frac{k_1}{6} + \frac{k_2}{3} + \frac{k_3}{3} + \frac{k_4}{6} + O(h^5)
\]  

(A.3)

The Runge-Kutta method was used for modelling the curvature of the muscle shape by calculating the angle at the bottom of the muscle structure, which produced a curve where the top touches the \( y \) axis at 0.0 or within a few hundredths either way. The model will take a “trial” run which crosses beyond the \( y \) axis, and another which does not quite reach the \( y \) axis, as shown in Figure A.4. From these, the final function, which will touch the \( y \) axis, is calculated.
Figure A.4: Graphical Representation of Runge-Kutta
Bibliography


[64] Berkeley Robotics and Human Engineering Laboratory. Berkeley robotics laboratory - welcome to the bleex project.


