A Soft-Inflatable Actuator for Children with Cerebral Palsy

Zoë Paton

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Supervisors: Dr Benny Lo and Rejin J. Varghese

Imperial College London

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Hamlyn Centre for Robotic Surgery - Department of Surgery and Cancer

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Abstract

Cerebral Palsy is the most common cause of motor impairment in childhood. Due to it being a permanent disability, there is a great social burden on society to treat them throughout their lives. Current treatments do not always provide the best outcomes and can leave the child unable to carry out daily tasks and they become dependent on others. This leads to a massive reduction in their quality of life. Current exoskeletons and exosuits have not been designed with children in mind and many of them are unsuitable due to the high torques that they produce. Therefore, the aim of this project was to design and test a soft-inflatable actuator that would be suitable for children and allow for flexion and extension of joints to occur. Through careful analysis of different materials and shapes, an air chamber design made out of polythene was selected. Through using Finite Element Analysis, it was possible to undertake pre-analysis to understand the behaviours of the proposed actuators. It was suggested that smaller air chambers contributed to greater ranges of movements being achieved. The actuators were then manufactured by using a heat-sealing press to form the individual air chambers. Static tests were carried out and it was found that the smallest air-chambers allowed for the greatest range of movement. Air slit size had little impact on range of movement, but the smaller air slit sizes did produce slightly better results than the larger air slits. The dynamic task used weights to understand how the actuators would react with external forces. The actuators struggled to move with weights attached with little to no movement with more than 5g added. A control system was developed, and a flex sensor enabled air to be pumped in and vacuumed out. By adding a straight actuator to the air chamber actuator, it allowed for flexion and extension to occur. To conclude, a novel actuator was designed, and good ranges of motion were achieved. However, the actuators need to have increased strength before they can be tested by human participants.

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Chapter 1: Introduction

1.1 Background

Cerebral palsy is the most common cause of motor impairment in childhood, with 2-3 of 1000 births being diagnosed with the condition(1). If the child is born prematurely or underweight, then the likelihood of being diagnosed increases(2). Cerebral palsy is caused by a perinatal or prenatal injury to the child's brain and leads to permanent limitations in movement, motor skills and muscle tone(3). Due to the young age at which cerebral palsy occurs and the fact that it is a permanent disability, the financial burden placed on society to treat them throughout their lives is particularly high and uses many of a countries' resources(4).

Children diagnosed with cerebral palsy require strategies to manage their symptoms, in particular help with walking and motor movements so that they are able to lead a more independent lifestyle similar to that of their peers. Thirty per cent of children with cerebral palsy are unable to walk and fifty per cent have an arm-hand dysfunction making these the most common form of motor impairments(5, 6). Severe motor impairments can put great strains on families and also limit the quality of life for the child. The International Classification of Functioning, Disability and Health suggests that cerebral palsy affects three different domains of functioning that all relate to each other(7). These are body function and structures (body domain), activities (individual domain), and participation (social domain)(7). Therefore, it is important to have solutions to help improve the body and individual domains which in turn will aid their symptoms and improve their social integration.

Currently, most children with cerebral palsy require either a wheelchair or a walker in order to be mobile (8). However, these limit the user and require constant assistance meaning they are unable to independently get around. Wheelchairs can also lead to further health implications as the muscles are not regularly used and can begin to waste away(9). This can lead to further mobility issues hence why it is important to have regular therapy and use assistive devices in order to improve their level of movement and ultimately allow for a more independent lifestyle to be achieved. For many families it is important that their child is able to walk and use their hands so that in later life it does not affect them in social situations and during physical activity(10). Early physical therapy interventions focus on the attainment of walking and use of their hands and arms, as the main goal of rehabilitation is to allow for autonomous living(10).

Manual rehabilitation can be very strenuous on therapists and is often insufficient so recently assistive devices have become more readily available(11). These allow for therapy to be undertaken more often as they can also be used in a home environment and can allow for more intense repetitive training to occur as the therapist is no longer required to undertake the physical therapy(12). This would suggest that there would be a greater consistency in the rehabilitation provided which should allow for more rapid improvements and quicker progression.

In recent times, robotic exoskeletons have been widely implemented in aiding in the restoration of function and mobility of patients. An exoskeleton is a wearable robotic mechanism that can provide mobility to the user through integration of the robot and the body into a single system(13). Actuators and built-in sensors are able to assist the limbs to undertake different movements and provide a certain level of support(14). The actuators enhance the strength of the user's joints allowing for a greater range of movements, such as walking and standing, to be achieved(15). Monitoring of the user's progress is also easier to track, and forces can continually be monitored as well as gait patterns. Therefore, throughout time, the exoskeleton should allow users to obtain higher levels of independence and have an improved quality of life.

Rigid exoskeletons have been well documented for the use of stroke and paralysed patients. They have been very successful in allowing those who are wheelchair bound to regain a sense of independence and be able to walk again(16). The ReWalk exoskeleton has been successfully shown to aid disabled users to undertake an independent lifestyle and allow for walking, going up and down stairs and other everyday tasks to be achieved(17). These rigid exoskeletons are particularly great for those who need full support in order to be able to walk as they are able to withstand large forces and maintain a constant structure for someone who cannot even stand up alone. However, for someone who needs slightly less assistance these can be particularly bulky and can in fact hinder the human motion and cause an unnatural gait to be obtained(18). This can cause further problems and injures hence be detrimental on recovery. One of the most common problems of these devices is the joint misalignment which ultimately leads to complications and negatively affects the user(19).

More recently, exosuits have begun to be developed. These offer a solution to the rigidity of the current exoskeletons whilst still being able to provide high power and being considerably lighter in weight for the user(20). Soft materials eliminate the issues of misalignment as they mould to the users' body and allow for a more one size fits all solution(20).

The majority of exoskeletons and exosuits that have currently been designed are for adults. There has been very little research undertaken for child specific exoskeletons (21). With cerebral palsy being the main cause of motor disability in children, it is paramount that exosuits are designed for them in mind to allow for aiding their rehabilitation from an early age and hopefully allowing for them to live a more normalised lifestyle.

1.2 Motivation

Due to the acknowledgement of the current limitations, an exosuit that is lightweight, child-friendly and provides a level of assistance to aid in their hand and leg movements would have a positive impact on their lives and help them to achieve autonomous living.

1.3 Aims and Objectives

1.3.1 Aims

The overall aim of this research was to design a soft inflatable actuator that is light-weight, low-cost, child-friendly and can provide movement assistance to the knee and hands of the user, hence meaning they have greater control of their hand and leg movements.

1.3.2 Objectives

The objectives of this study were:

(1) Carry out an extensive literature search on the currently available exoskeletons and exosuits and critically review them;

(2) Research the specific requirements and needs of a child with cerebral palsy;

(3) Develop a design criterion based on the needs of the user;

(4) Design prototypes;

(5) Test movements and weight bearing capability of each prototype;

(6) Design a control system for inflating the actuators;

(7) Suggest applications for the use of the actuators.

1.4 Thesis Structure

The Literature Review (Chapter 2) will investigate the currently available exoskeletons and exosuits, as well as how soft materials could be utilised in rehabilitation. The gait and movement of the hands and knees will also be discussed.

The Conceptual Design, based on what was found in the literature review, will be discussed in Chapter 3 along with the 3D designs and finite element analysis results.

Chapter 4 will discuss the manufacturing of the actuators with Chapter 5 discussing the methods and results of the static testing. This will then lead to Chapter 6 which will discuss the methods and results of the dynamic task.

The control system for inflating and deflating the actuators will be discussed in Chapter 7 and the applications for where these actuators could be implemented will be discussed in Chapter 8.

Chapter 9 will discuss the results found and the future work with Chapter 10 presenting the concluding remarks from this study.

Chapter 2: Review of the Literature

2.1 Introduction

The boundaries of motor performance are continually being pushed and with the development of exoskeletons and exosuits these are allowing for new outputs, such as increased strength, restoration of ambulatory capabilities for paralysed patients and assisting stroke sufferers, to be achieved. However, these have currently been achieved with heavy, rigid, metal devices. The inherent advantage of using metals are that they provide good strength and deliver high forces to the user but unfortunately, they create a significant inertia which alters human movement and can cause further injuries(19). They are also complex as they need to be designed on a case by case basis so that they are properly aligned to the biological joints of the user. Another issue with exoskeletons is that they are indiscreet and for some users they would not want to wear them for this reason.

Due to the reasons discussed above, soft materials have started to be utilised so that they are more discreet, work in parallel with the body and are more of a 'one size fits all'(20). Soft exosuits have been developed to act more as external muscles instead of an external skeleton. Research into exosuits is currently more limited but appear to have a promising future in aiding rehabilitation of patients.

The rest of this chapter will discuss the needs of someone who suffers with cerebral palsy, the structure and biomechanics of the knee and hand to ensure the exosuit is capable of aiding these joints and lastly it will discuss what exosuits are currently available and what limitations they may have.

2.2 Cerebral Palsy

Children who suffer with cerebral palsy have abnormal motor behaviour which results in a limitation in the activities that they are able to undertake. Cerebral palsy is typically diagnosed in the second year of their life, so in an ideal situation, treatment should begin at this point to result in the best possible outcome since cerebral palsy has no cure(5). Research has suggested that children who can achieve gross motor skills by two years of age have an increased outcome of being walking independently between three and five years(22). This signifies the importance of starting rehabilitation as early as possible. Spasticity of the muscles leads to shortening of the musculoskeletal units which causes deformities and difficulty in controlling movements of limbs. 88% of children who have cerebral palsy suffer from the spastic form(23). This suggests that most children with cerebral palsy struggle with performing movements so hence there is a great need to provide support to allow for a greater quality of life to be achieved.

Effective management of the physical disabilities is essential in improving the quality of life of the child and allowing for a more normalised life to be achieved. A quality of life study carried out on 8-12-year olds who suffer from cerebral palsy suggested that self-mobility and easing of pain were the main contributors to an improved quality of life(24). Through the use of rehabilitation this is possible to be achieved. Currently there a lot of different management techniques used to help those with cerebral palsy. Typically, children who struggle to walk will use mobility aids such as wheelchairs or a k-walker which can be seen below in Figure 2.1. K-walkers are useful in aiding a child to stand and being able to move, however, they are bulky and limit their ease of moving around.

Figure 2.1. An example of a k-walker used for children with cerebral palsy (25)

Another form of managing cerebral palsy is through the use of physiotherapy. Physiotherapists can provide tailored programmes for each individual which can be beneficial in improving the certain needs that the child may have. However, physiotherapy can only be undertaken a few times a week which is not enough to make significant changes on the outcomes of the child. Parents can learn how to undertake the movements themselves but if these are delivered incorrectly then this can cause more harm than good. The effectiveness of physiotherapy has been debated. Some studies suggest that it can improve strength and function of individuals without having negative effects on the patient(26,27). However, other studies suggest that the majority of interventions that use physiotherapy have limited overall outcomes(28).

Orthoses have commonly been used for the ankle-foot to help straighten the leg and allow for an improved walking technique. These help to maintain a certain foot position and reducing the bending of the knee (crouch gait) which is commonly seen in patients suffering from cerebral palsy. They have also been suggested to prevent the progression of joint contractures(4). There is, however, very little evidence to suggest that they are effective in improving walking gait long term as the muscles of the leg rely on the orthoses and do not strengthen appropriately in order to walk without them(29).

Another treatment that has been used in patients with cerebral palsy is the use of botulinum neurotoxin type A injections. These help to block the release of acetylcholine at the neuromuscular junction which in turn reduces the spasticity of the muscles. They are long lasting (three-four months) and can be used in combination with physiotherapy which has been shown to improve the gait and movement of the patient as the muscles are able to work more effectively(30). However, this is an invasive procedure which some people may not want and the long term effects of using the treatment are still relatively unknown.

Due to lack of repetitive motor tasks and higher level of coordination required, finger movements are more challenging to retrain in comparison to the lower limb. With fifty percent of children with cerebral palsy having a hand dysfunction it is paramount that there are management techniques to aid their hand function(6). Currently, most research focuses on walking as this is seen to be more important for improving quality of life. However, having good control of your hand movements is as equally important in being able to lead a more normalised lifestyle. The use of corrective surgery in children with cerebral palsy has also been found to not be as effective in the upper limb as the lower limb which results in them not using their hands and unable perform essential tasks(31).

More recently, it has been suggested that rehabilitation of the hand should focus more towards undertaking tasks that they would perform in a real-life environment as opposed to standardised tasks that would normally be practiced (32). There is good evidence that suggests that this type of rehabilitation improves the functioning of the hand (33,34).

Current rehabilitation techniques have limited effectiveness in improving the lives of those with cerebral palsy, hence it is important to find new methods to help achieve the independent lifestyle that they desire. A device that could help them in day to day life, to achieve real-life tasks would greatly improve their quality of life.

2.3 Hand

An understanding of the hand anatomy and biomechanics is fundamental in being able to design a suitable device for aiding in the functioning of the hand. The next two sections will discuss the anatomy and biomechanics of a healthy hand.

2.3.1 Anatomy

The hand has a complex anatomy and has to be capable of performing many different movement patterns. The hand is essential in being able to perform daily tasks and any problems can make simple objectives particularly challenging. It has been suggested that the thumb contributes to 40% of hand function which makes it an important part of the hand in allowing for full functionality(35). The hand and wrist are made up of 27 bones, 8 carpals, 5 metacarpals and 14 phalanges which can be seen below in Figure 2.2. The human finger consists of three joints: distal, proximal, and metacarpal interphalangeal joints(36). It is important that any rehabilitative device has a similar structure to the fingers to allow for optimal movement to be achieved.

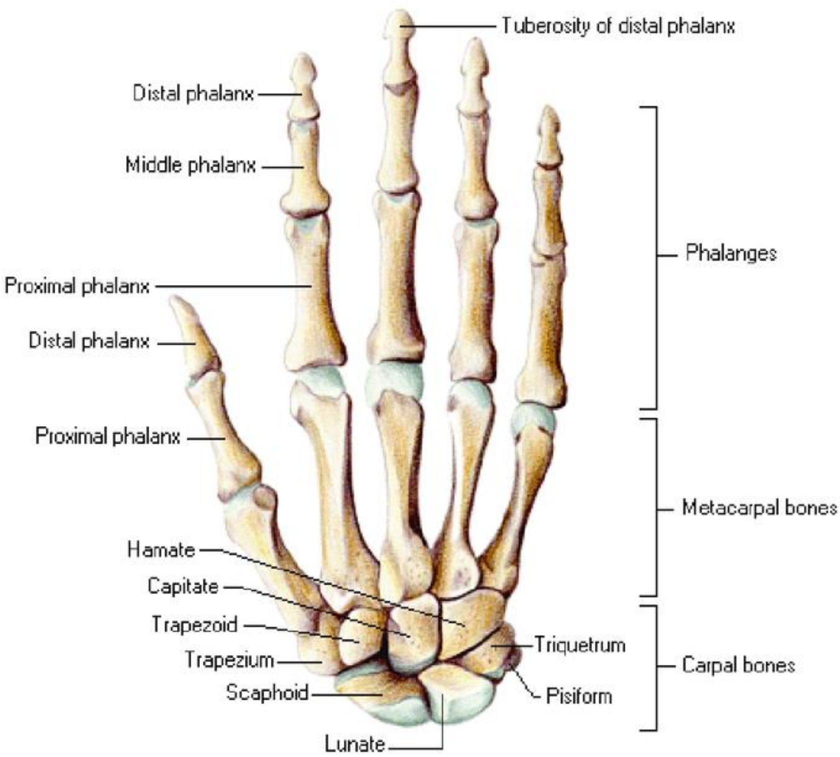


Figure 2.2. *Anatomy of the hand* (37)

2.3.2 Biomechanics

The hand has 27 degrees of freedom with four in each finger. Three of which are for extension and flexion and one for abduction and adduction. The thumb is different with five degrees of freedom(38). The movements of the fingers are controlled through extrinsic and intrinsic muscles. The metacarpal interphalangeal joints have a flexion range of between 70° and 95°, with the distal interphalangeal joints having maximum flexion of 100° and the proximal interphalangeal joints having 90°(36). It is important than a rehabilitative device is able to achieve similar ranges of motion to these so that the best therapy can be delivered to the user.

2.4 Knee

2.4.1 Anatomy

The knee joint has three articulations, one between the femur and patella and two between the femoral condyles and tibial plateaus as seen in Figure 2.3. There are multiple ligaments that help to keep the knee in place and allow for movements to occur. The most important ones being the anterior cruciate ligament and the posterior cruciate ligament. The knee is a complex synovial joint that has to be able to bear body weight. If the knee is weak then it can lead to major disabilities and ambulation can become very challenging. Any exosuit must be able to cope with assisting in bearing body weight and hence must be strong in order to have a significant impact on the user.

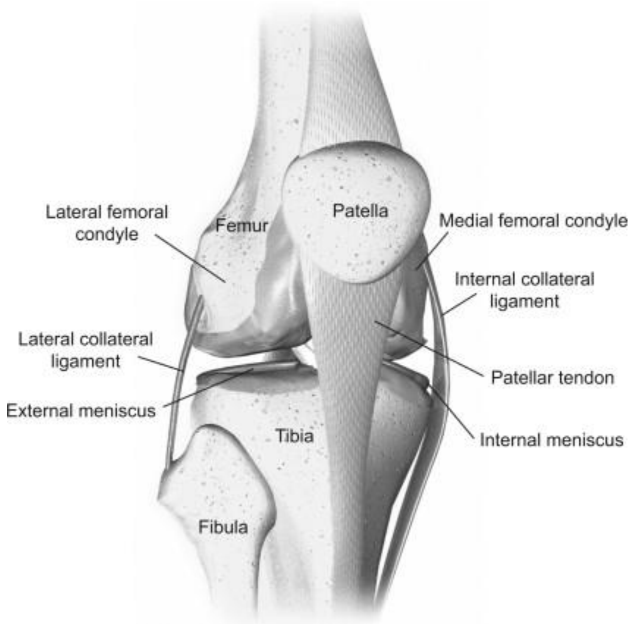


Figure 2.3. Anatomy of the knee (39)

2.4.2 Biomechanics of the Knee

The knee joint has six degrees of freedom and can undergo flexion and extension as well as mediolateral translation, Varus-valgus angulation and internal/external rotation(40). The knee can flex between 120° and 160° and can extend anywhere between 0° and 15°(41). When the knee is as at a right angle, the tibia is able to laterally rotate 40° and medially rotate 30°(41). Due to the complex nature of the knee, a soft exosuit would be better for knee movements so as to not constrain the leg in a certain position which could result in further injuries.

2.5 Exoskeletons

Currently there a wide variety of exoskeletons available to assist patients with ambulatory issues as well as with upper limb impairments. Exoskeletons are designed to act as external skeletons to help support the human body. These will now be discussed in the following two subsections.

2.5.1 Upper Limb

At present, there are a number of commercially available upper limb exoskeletons. Most of these focus on rehabilitating movement of the arm for patients who have suffered strokes. These exoskeletons match the joint structure of the upper limb to allow for similar movements to that of a healthy arm. Exoskeletons are able to provide physiotherapy and therefore replace the manual work that a physiotherapist would normally undertake. This allows for greater consistency in the training as well as a greater amount provided as the physiotherapist would not become fatigued(12). This should increase the speed of motor improvements as the arm would be subjected to more training. Exoskeletons can improve the range of motion of the affected limb and once this has been restored then force training can be introduced to increase the functionality of the limb(42). Through the use of multiple interfaces, it is possible for the exoskeletons to control the torques applied to each of the joints. This means that is possible for muscle specific therapy to be achieved through targeting different muscles with individual torques(19). Virtual reality has also been incorporated into upper rehabilitation with the users having to pick up virtual objects whilst using an exoskeleton. This can make rehabilitation more fun whilst also strengthening the joints to be able to undertake certain movements. It has been shown to have supplemental benefits for stroke patients(43). However, this can only be used in a laboratory setting so would not be able to be used on a regular basis.

The main challenge of exoskeletons is incorporating enough degrees of freedom to allow for a good range of movement to be achieved. More recent exoskeletons have attempted to incorporate more so a greater variety of rehabilitation can be undertaken. The IntelliArm (Figure 2.4) has seven active and two passive degrees of freedom and was designed to be more anatomically correct(44). Most exoskeletons have successfully covered the shoulder, elbow and wrist but at present none incorporate the fingers which does not help with achieving activities that are associated with daily living. Due the number of degree of freedoms found in the fingers, it is difficult to match these in an exoskeleton (29).

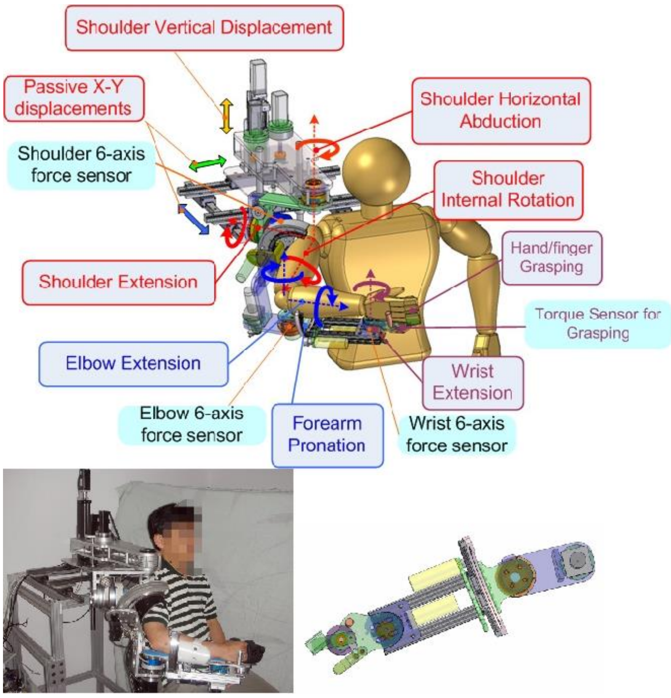


Figure 2.4. The IntelliArm (41)

Currently, the number of hand exoskeletons is very limited. Due to the complex nature of the hand, and the size of the joints it makes it very challenging to mimic this and correctly align an exoskeleton to the hand. Also, the size of hands and fingers varies which make it considerably more challenging to fit an exoskeleton to more than one person. CAFE (cable actuated finger exoskeleton) has been developed to perform individual control of each finger(45). However, this is extremely bulky and is unable to help with performing everyday activities. At present, any of the upper limb exoskeletons that have been developed are for adult users. This is mainly because designing an exoskeleton small enough to fit on a child's hand is challenging and hence there are currently none to aid children with cerebral palsy.

2.5.2 Lower Limb

Lower limb exoskeletons have been focused on more than upper limb exoskeletons hence they are more readily available. They have been designed to allow those who are paralysed and cannot walk to regain this ability and also help those who have severe issues with ambulation such as after a stroke(18,46). These types of exoskeletons are formed of rigid structures with mechanical links. It is these rigid structures that result in the exoskeleton not being fully compatible with the human body(47). A lot of lower limb exoskeletons still need the use of crutches to aid balance. They are also extremely costly and often the batteries do no last for more than a few hours making them not useful for long daily use(17).

One lower limb exoskeleton does currently exist for children with cerebral palsy as seen below in Figure 2.5. The challenges with lower limb exoskeletons for children are that they are trying to train a different walking style rather than just restore walking capabilities. This exoskeleton was found to significantly reduce crouch gait in children and adolescents with cerebral palsy, with results being similar or better than surgical outcomes(48). They also found that the exoskeleton was safe for the children to use. This suggests that with an appropriate device and regular therapy, non-invasive methods could help to improve mobility of those suffering from cerebral palsy. They could be used as the sole rehabilitation method or in conjunction with the pre-existing methods to achieve the best outcomes possible, however more devices need to be designed for children to see the real benefits that they may have.

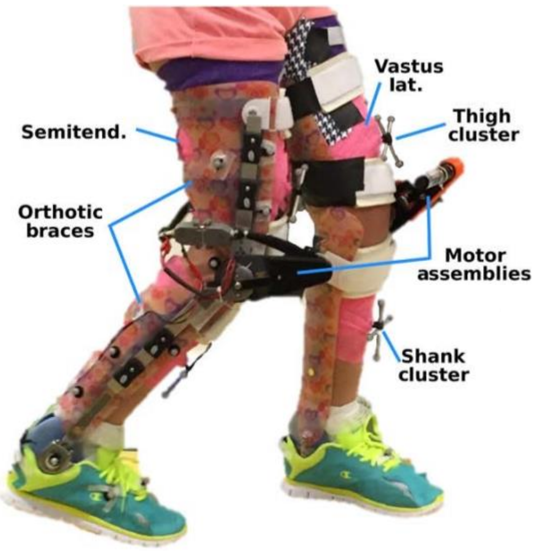


Figure 2.5. A lower limb exoskeleton for children with cerebral palsy (48)

2.5.3 Problems with Exoskeletons

Exoskeletons require custom fittings to the participant, and some can take a few sessions before they are appropriately fitted(49,50). If any changes occur to the patient, then refitting would have to be redone which can be quite time consuming. If the exoskeleton is not appropriately aligned to the body, then undesirable interaction forces may be created, and inaccurate sensor measurements may occur(19). Some exoskeletons only allow for repetitive tasks to be conducted which may not be optimal in rehabilitation. Exoskeletons are extremely bulky and heavy so are not very suitable for children and as they are not discreet some children may feel embarrassed by them and not want to participate in social activities which will reduce their quality of life. Also, the high torques that exoskeletons can produce will not be suitable for small children and could result in injuries occurring(18). Exoskeletons are typically quite expensive and for a child who is growing a new exoskeleton would be needed regularly which would be very costly for the family. Another point is that a lot of these exoskeletons can only be used in a laboratory setting and hence means that they would not be able to have constant therapy which would produce slower improvements in their motor control. Due the reasons discussed in this section; a rigid exoskeleton would not be suitable for children with cerebral palsy who need more regular therapy in order to be able to undertake daily activities.

2.6 Exosuits

Due to the current problems that exoskeletons face, soft exosuits and soft robotics have begun to emerge with varying applications within rehabilitation, grasping and manipulation(51). Many of the devices that are designed are bioinspired. The current upper and lower limb exosuits will now be discussed.

2.6.1 Upper Limb

As discussed previously, the hand is particularly complex and producing a suitable exoskeleton is challenging. Soft materials have revolutionised hand exosuits as they can conform perfectly to the shape of the hand hence also minimising the restrictive nature of the device and making them more practical. Hand exosuits, also known as soft wearable gloves, are important for assisting in activities associated with daily living(52). Typically, soft wearable gloves are made of fabric or plastic. An advantage of using soft materials like these, are that they are lightweight and compact which increases the comfort for the user.

Tendon-driven mechanisms have commonly been used for the actuation of the glove. The tendons pass over the fingers and allow for multiple motions to occur(53).This method has been shown to aid in performing daily tasks(54). Another method of actuation is through the use of pneumatics. Through the use of different layered materials to control the strain of the actuators, expansion of the air chambers can occur in a specified direction. The Wyss Institute glove uses this technique(55). This allows for flexion of the fingers to occur. The use of ridges in air chambers can also cause the actuators to curl once pressurised with air(56). However, this design has been suggested to only have mediocre gripping force. Some examples of soft upper limb exosuits can be seen below in Figure 2.6.

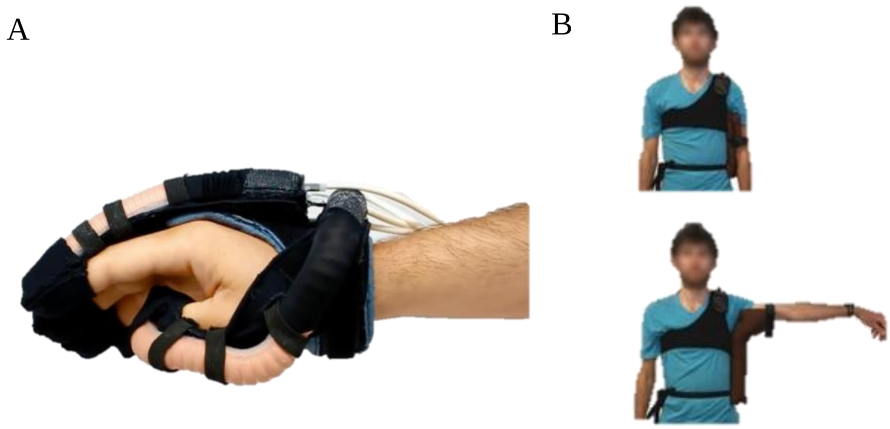


Figure 2.6. *(A) The Harvard Glove with Reinforced Fibres (57) ; (B) A Shoulder Abduction Exosuit (58)*

2.6.2 Lower Limb

Lower limb exosuits have focused largely on improving and aiding the performance of healthy users in order to reduce their energy expenditure, in particular in military use. It has been suggested that during walking, a tendon-driven exosuit can apply moments to the hip and ankle of 18% to a healthy adult (Figure 2.7A)(20). They were found to be comfortable and not to constrain any of the degrees of freedom in the leg which is a considerable benefit of exosuits when compared to exoskeletons.

Other studies have suggested that pneumatic actuators are able to provide 25% of the knee moment during the swing phase in a healthy male which suggests that pneumatics are capable of providing support to those who struggle with ambulation (Figure 2.7B)(59). The device was also very lightweight and by incorporating sensors was able to assist during the gait cycle to allow for aiding in the extension of the leg.

It is clear to see that soft exosuits have a promising future in aiding those who struggle with motor movements by providing a certain degree of help to them. The lightweight, unrestrictive designs also make them much more user-friendly than exoskeletons. Therefore, soft materials would be preferred when designing a child therapy device.

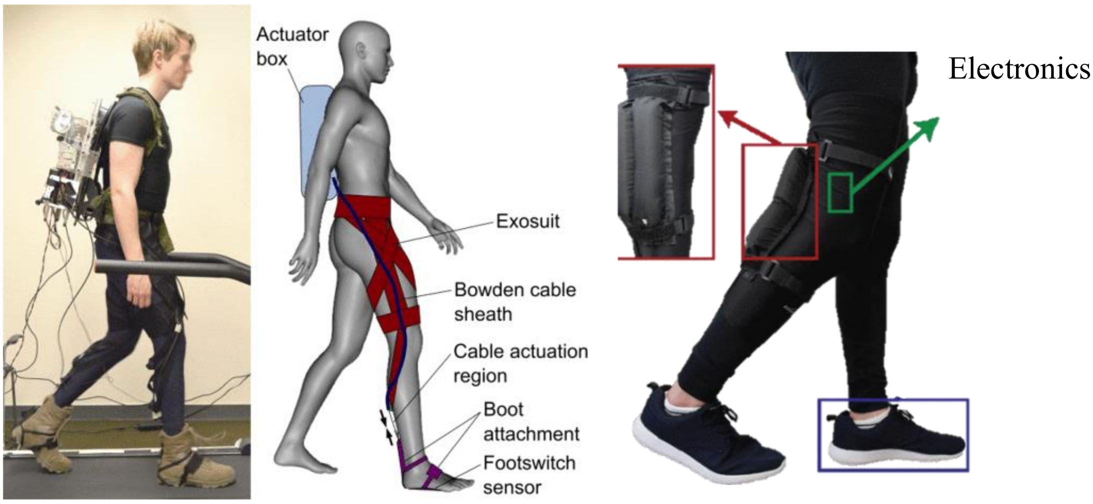


Figure 2.7. (A) A Tendon-Driven Exosuit (20); (B) A Soft-Inflatable Exosuit (54)

2.7 Control Systems

The control systems for exosuits are either low-level or high-level. Low-level control allows for the force, torque and position to be controlled and consists of a basic control loop(60). High-level control has the added benefit of being able to measure the exosuit as well as the environment so can make changes accordingly. This means that more accurate forces are delivered so that the task in-hand can be successfully executed(60).

Current actuators in exosuits are mainly tendon-driven or use pneumatics in order to produce movement. Tendon-driven actuators are typically placed on the top of the exosuit, whereas pneumatic actuators are usually fabricated within the exosuit. One advantage of pneumatics, when compared to tendon-driven actuators, is that the pressure is distributed evenly over the joints as opposed to forces acting more in one certain area which may not have as good rehabilitative outcomes(61). However, pneumatics requires a compressor in order to provide that air flow and these can be heavy and are not able to be carried around by the user(62). This limits their use solely to rehabilitation and therapy as opposed to helping users achieve everyday tasks. Pneumatic actuators in the NUS glove have been shown to provide good therapy for stroke users and hence could also be suitable for children who have cerebral palsy(63). Another limitation of pneumatic actuators is that they need a constant supply of pressure in order to keep joints in a certain position(64). This can be challenging when attempting to grip an object as if the pressure is lost then the task cannot be achieved. Tendon-driven actuators are able to maintain the same tension in the cable which allows for less power being needed for maintaining certain joint positions(65). The output forces of the pneumatics are considerably lower than that of the tendon-driven actuators which could result in them being a safer option for use in young children.

2.8 Summary

In summary, this literature review has discussed the requirements of a child with cerebral palsy and what current rehabilitative methods are available for them. The finger and knee anatomy and biomechanics were then discussed to understand how these joints would move if they were healthy. Then the current exoskeletons and exosuits were discussed to understand what is currently available and how they could be improved.

The next chapter will discuss the conceptual design and the methods used to create a successful prototype.

Chapter 3: Conceptual Design

3.1 Introduction

As previously discussed, this project aimed to design a soft-inflatable actuator that could be used on the knees and finger of children with cerebral palsy to aid them in moving their joints and performing everyday tasks more easily. It was essential that the actuator was made of soft materials so that it would be suitable for children and eliminate the risks of rigid exoskeletons that were discussed in the previous chapter.

This chapter will cover the cover the important elements that the actuator must meet in Section 3.2, as well as how materials and shapes were explored to aid in the design strategies of Section 3.3. The conceptual designs that were formed from the design criteria and strategies will then be presented in Section 3.4, along with 3D models and finite element analysis evaluating how the actuators would be predicted to move in Section 3.5.

3.2 Design Criteria

The design criteria for the exosuit is as follows:

1. The actuator must be lightweight
2. The actuator must not restrict the user when not in use
3. The system must be low cost
4. The actuator must be robust
5. The actuator must be flexible
6. The actuator must bend to match the profile of the finger/knee
7. The control system needs to be able to pump air in and also vacuum out
8. The actuator must be suitable for young children
9. The actuator must be able to assist the flexion and extension of joints

The actuator must be lightweight so as not to restrict the user's movement and cause added fatigue from wearing an exosuit. Being lightweight is also important as small children will not be able to carry heavy weights as their bones are still developing and this could lead to further health problems.

The actuator must not restrict the user's movements so as to allow for the them to move their limbs normally and not be forced to move in a certain way which could potentially cause injuries if they are moving incorrectly and not aligned with the device.

The device is being designed for children so it is essential that the system is low cost as they are continuously growing so will need larger actuators as they get older. By having low cost actuators, it means that they can be made at different suitable sizes so that they can still use the device as they grow.

It is essential that the actuator must be robust yet still flexible. It needs to be robust so that it does not split easily and can support the weight of the knee and fingers. However, it still needs to flexible so that it can fully bend and allow for a full range movement of the joints.

The actuator movement patterns but be similar to the profiles of the finger and knee so that the actuator can aid successfully and allow for full flexion and extension to be achieved.

3.3 Design Strategies

To ensure the suitability of the actuators for use in aiding finger and knee movement in children, a few design considerations were looked at. These included the materials used for the actuator, the shape of the actuators to allow for bending, and looking at ways to control the actuators. These will be discussed in the following sections.

3.3.1 Materials

The actuator needs to be lightweight yet strong so that it can cope with the weight of limbs and support their movements. There are a variety of materials currently used in soft actuators and these will now be discussed.

At present, a number of soft actuators are made out of polythene sheets that have been heat sealed into different sizes and shapes(59). The advantage of using polyethylene sheets are that when they are deflated, they are completely flat and flexible so do not restrict the user when they are not in use. Once they are inflated, they become rigid and can no longer be easily deformed. They are extremely lightweight and also cheap with no complex manufacturing needed to turn them into actuators. As they are not too powerful, they can be considered fairly safe as no extreme forces would be applied to the body. This would make this type of material ideal for children so that injuries and accidents can be avoided. Depending on the thickness of the sheets then they can be quite strong and have been shown to provide 25% of peak torque to a male's lower limb whilst walking(59). When reinforced within a fabric pocket they become even stronger and this ensures the actuators do not deform and can provide maximum support to the user. However, they are not able to provide full support to a user and hence would not be suitable for use in severe mobility issues. They can also have problems with leakages and bursting if the density is not appropriate, so it is important that the correct density is selected in order to be strong enough to cope with the demands they are required for.

Other soft actuators have been made of canvas materials(66). Canvas provides greater strength than polyethylene. Some studies have combined polythene sheets with canvas to give added strength to the balloons(59). However, having tested canvas it was noted that although they were strong, they did not allow for flexible movements to occur. They did not allow for any bending movements so would not be suitable for aiding in flexion of the knee or finger. They would, however, be useful for extension due to their increased strength. Another downfall of canvas is that they must be coated in order in to make them fully airtight. Also, manufacturing canvas into different shapes is more challenging and takes more time to seal the designs fully.

The last material that will be discussed is silicone rubber. Silicone rubber has been used in soft wearable gloves(67). Due to its flexibility it can match the profile of the finger and aid in flexion. By implementing ridges into the silicone, a bending movement can be produced(67) . It is also very cheap which allows for them to be fitted to the individual. However, manufacturing time is longer when using silicone as moulds need to be created and the silicone needs to be cured in order to achieve the desired shape.

Table 3.1. Ranking of Materials for Suitability in Actuator

	Polythene Sheet	**Canvas**	**Silicone**
Lightweight	1	3	2
Low Cost	1	3	2
Flexible	1	3	2
Robust	3	1	2
Unrestrictive	1	3	2
Aid Flexion	2	3	1
Child Friendly	1	3	2

The above table ranks the materials that have been discussed between 1-3 (with 1 being best and 3 being worst) on the different qualities that are important for this actuator. Based on the rankings of the materials as seen in Table 3.1, polythene would be the most suitable material for the use of this actuator.

3.3.2 Shape

The shape of the actuator has a direct impact on what movement range will be able to be obtained by the joint. Hence it is important to mimic the natural range of movements for the joints so as not to restrict the user and allow for full range of movements to be achieved. Therefore, the shape of the actuator is extremely important in fulfilling this requirement. The different shapes that can be seen in Figure 3.1 were trialled in order to understand their movement capabilities, the following information was found.

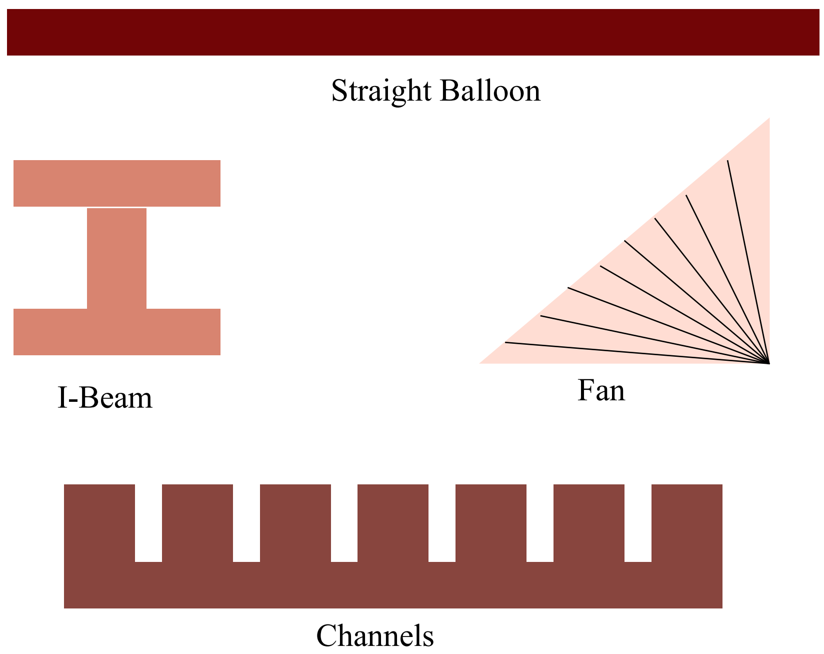


Figure 3.1. Different shapes that were trialled

The straight balloon designs were found to be quite strong due to the simple manufacturing methods. However, they provided no support for flexion as when they were inflated, they extended and became rigid. Hence these would not be useful in the flexion part but could be used for extension of a joint.

An I-Beam balloon is two straight balloons attached together. They have been found to provide greater strength than one single straight balloon alone(59). However, once they are inflated the can become quite bulky which would not be suitable for a finger but would be for the knee. Again, they have the same problem of not aiding in flexion so would not be suitable.

A fan shaped design, based on an accordion, was also trialled. This presented a good way of aiding flexion as well as extension. The pleats create a method of extending the device that aid in the extension of the finger and by folding the pleats, flexion could occur. This issue with this shape is that at rest the device would be bulky so would not be able to be worn at all times which could restrict what the user was able to undertake.

The last shape that was trialled was the use of channels. Other exosuits have used similar designs and have found these to be very useful at providing bending movements(67). Through changing the channel sizes, it allows for different degrees of flexion to occur. This would suitable for aid in finger or knee extension. Also, when not in use the device would be flat and would not inhibit the user.

This would suggest that a design incorporating channels would be best suited for this actuator.

3.3.3 Control System

Based on the research undertaken in the literature review, a pneumatic system would be best suited for a child exosuit. A suitable control system is required in order for the actuators to work effectively and efficiently. Due to the weight of most control systems, an off-board design would be better suited for children so that they do not have to carry extra weight which could result in fatigue and injuries. The system requires a pump and vacuum in order to get air in and out of the actuator quickly so that the finger or knee can be aided in flexion and extension. The pressures provided should be low so as not to cause injury to the user. An emergency button should be incorporated for safety in case any issues arise.

3.4 Conceptual Designs

Based on the design criteria and the research undertaken into different materials and shapes, a conceptual design of the actuator was formed. The initial design was formed on SolidWorks (SolidWorks Corp., MA, US) so that pre-analysis could be undertaken before manufacturing the design. The material chosen on SolidWorks was the polythene low density film as this material would be best suited for the application it is intended for and closely matches the material the actual actuators would be manufactured from. Based on the research undertaken on the shape, air channels would be best suited for helping mimic the bending seen in the finger and the knee. From this, the design seen below in Figure 3.2 was created.

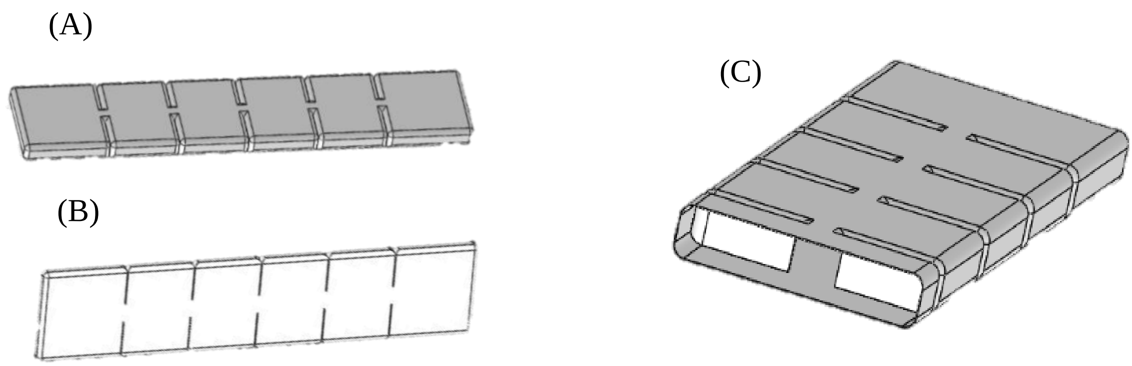


Figure 3.2. (A) Top View; (B) Bottom View; (C) Cross-Section of Actuator Design

The design seen in Figure 3.2 shows a different top and bottom design. The top has channels for the air so that there will be an increased surface area which will encourage a bending effect of the actuator. The design is completely hollow with just a thin layer of film (0.19mm) on the outside. The gaps are where the design would be heat sealed to form pockets of air to again help cause a bending effect.

To test which size air chamber would be best, air chamber sizes of 2cm, 3cm, 4cm and 5cm were designed so that finite element analysis could be undertook to see how they may affect displacement and stresses on the actuator. Different sized air slits were also designed and tested to understand if these had an impact on the capability of the actuator. The air slit designs all had the same air chamber size of 5cm.

3.5 Finite Element Analysis

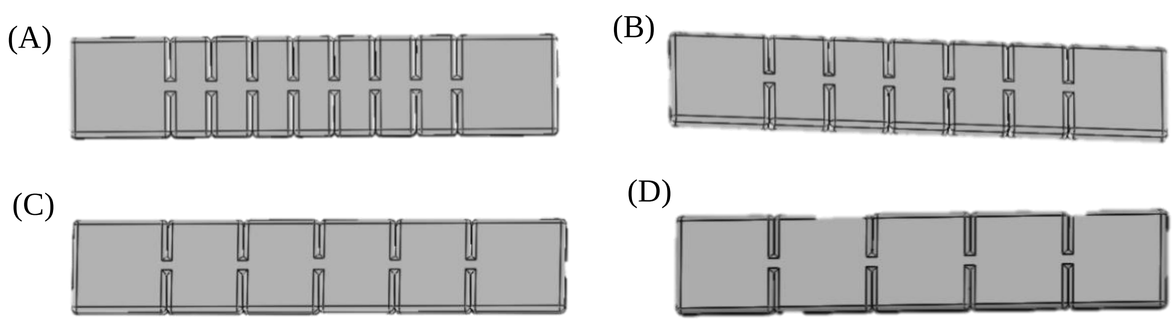


Figure 3.3. (A) 2cm; (B) 3cm; (C) 4cm; (D) 5cm Air Chamber Designs

The different air chamber actuators, that can be seen above in Figure 3.3, and the different air slit sizes underwent finite element analysis in SolidWorks to gain an understanding of the stresses, strains and displacement that may be experienced by the actuators. The actuator designs were finely meshed to improve the accuracy of the results. The actuators were fixed at one end to mimic a clamp. The pressures were applied to the inside of the actuators to mimic air flow. Pressures of 500N/m^2 to 3000N/m^2were used to test the actuators and to see how they coped at different pressures. An example of the finite element analysis can be seen below in Figure 3.4. The finite element analysis suggests that when the actuators are pressurised that they will bend in the correct direction, away from the top piece. This suggests that the increased surface area does create a bending effect.

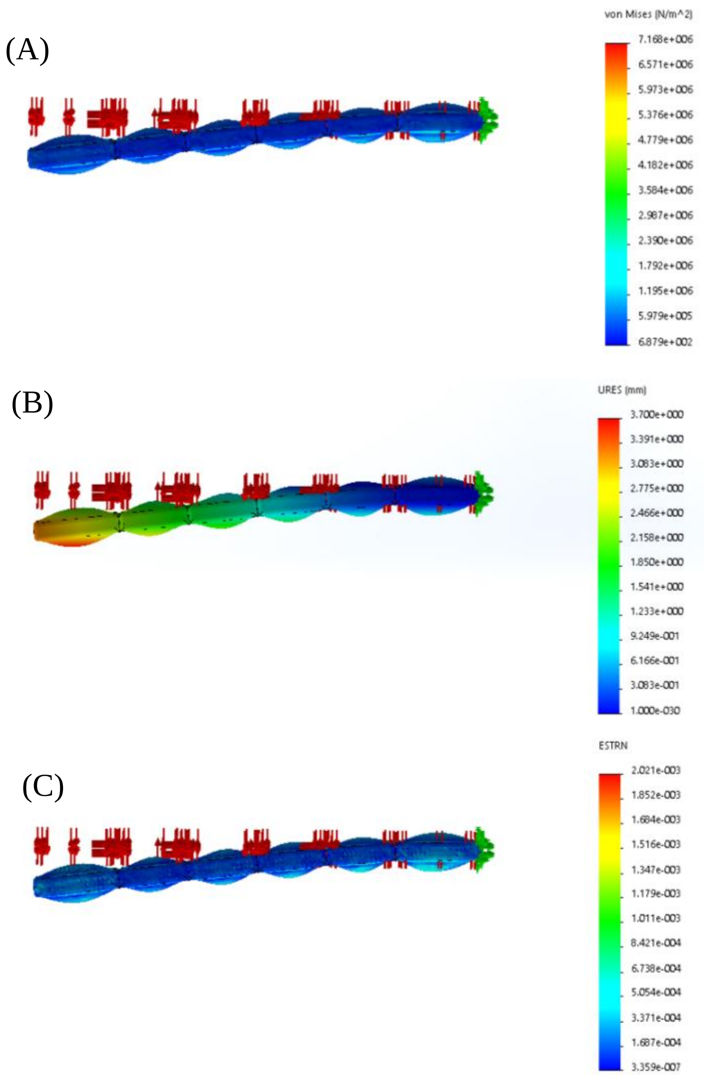


Figure 3.4. (A) Stress; (B) Displacement; (C) Strain in the 4cm Air Chamber Actuator with 500N/m2 of Pressure

The results for stress, strain and displacement for each of the air chamber actuators at different pressures can be seen in the below graphs.

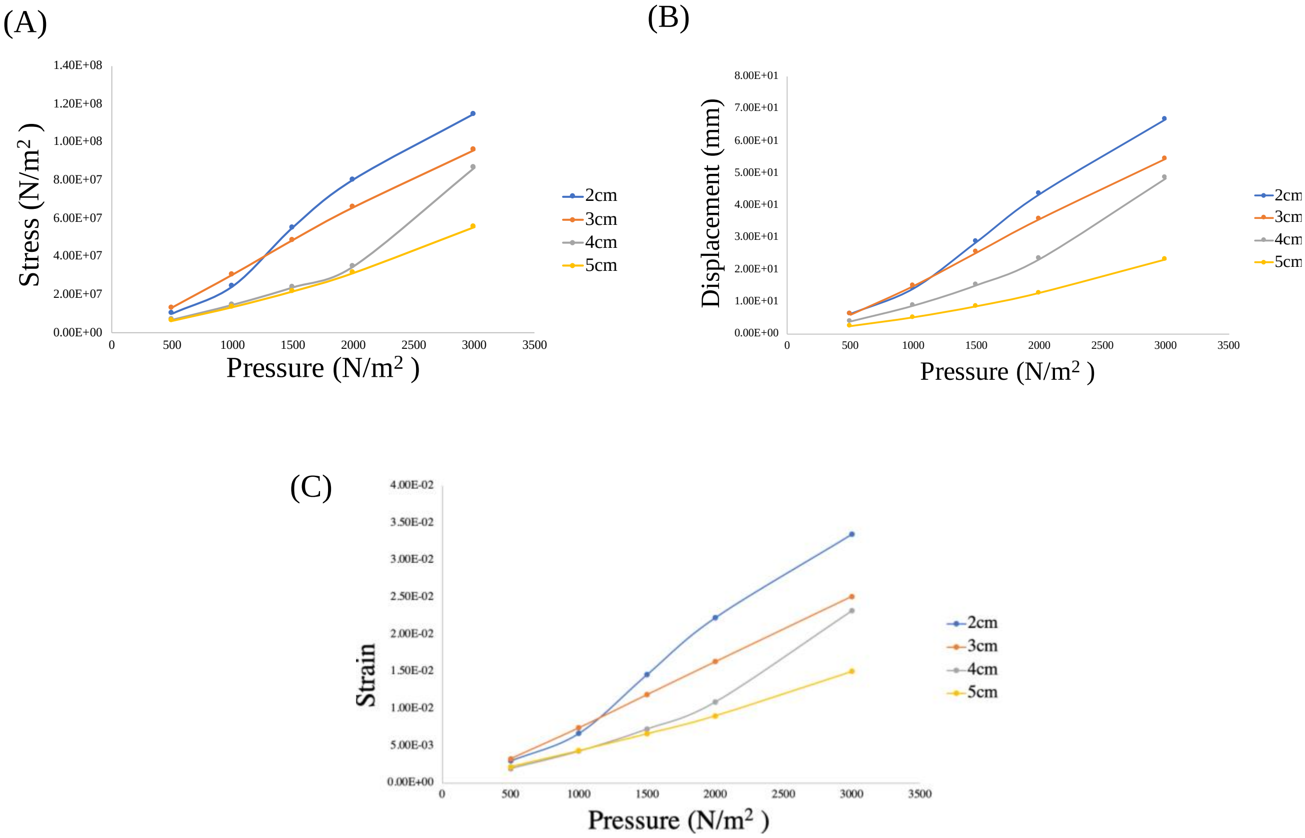


Figure 3.5. (A) Stress; (B) Displacement; (C) Strain Results for Each Air Chamber Actuator at Different Air Pressures

The results for the different air chamber actuators would suggest that the smaller the air chamber size, the greater the amount of displacement achieved. This could suggest that the 2cm air chamber actuator will have the greatest range of movement and the 5cm air chamber actuator will have the smallest. However, because the smaller air chamber sizes have greater displacement, they also have higher strain and stresses. This could result in failure or bursting of the actuators.

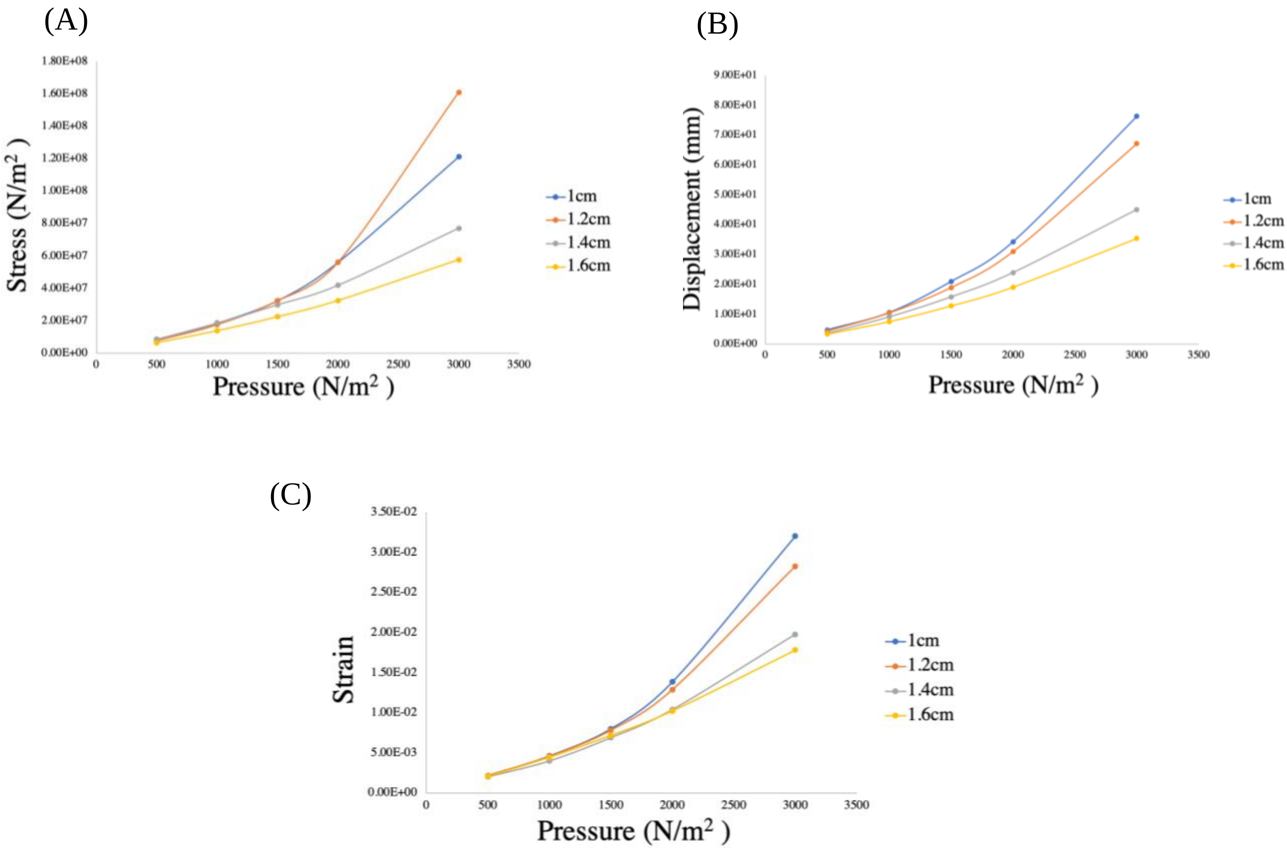


Figure 3.6. (A) Stress; (B) Displacement; (C) Strain Results for Each Air Slit Actuator at Different Air Pressures

The results for stress, strain and displacement for each of the air slit actuators at different pressures can be seen in the above graphs in Figure 3.6. The results for the different air slit actuators suggest that the smaller air slit sizes allow for the greatest displacement, with the largest producing the least displacement. Again, because of the greater displacement, they also have the greatest stresses and strains. Because the gaps are smaller there will greater pressure put on them which could lead to bursting.

3.6 Summary

In summary, this chapter has discussed the best material and shape for the actuators. Polythene sheets with air chambers are the most suitable for the purpose that they are intended for. The finite element analysis allowed for pre-manufacturing analysis to understand the movements that could be expected by the actuators. The results suggest that smaller air chambers and air slit sizes would be best for achieving greatest movement. The next chapter will discuss the manufacturing of the actuators and the equipment that was required.

Chapter 4: Manufacturing of Actuators

4.1 Introduction

In the previous chapter, the design criteria and strategies were discussed, and the conceptual designs of the actuators were created in SolidWorks and Finite Element Analysis was undertaken to gain an understanding of the movements that would be experienced at different pressures. Based on these findings, the following actuators were manufactured. This Chapter will present the manufacturing techniques used to make the actuators and the different actuators that were made.

4.2 Equipment

In order to manufacture the actuators, the following equipment was required:

- Handheld heat sealer
- Glue gun
- Air pipe
- LFT2500STK Clear Polythene Layflat Tubing – 2” x 500 gauge

4.3 Manufacturing

When manufacturing the actuators, the polythene tubing was cut into lengths of 25cm. Four actuators were created with different sized air chambers and five actuators were created with differed sized air slits. All of the actuators were heat sealed on the same side of the polythene to allow for a greater surface area on the top to create the bending effect. If the actuators were heat sealed on alternating sides, then a twisting effect was caused which was not desired. Each actuator had an air tube in the top which was heat sealed around and then glued to ensure that no leakages would occur. The bottom of all of the actuators were completely sealed with the heat sealed to fully seal the actuator and make them airtight. The manufacturing of the different actuators will now be discussed.

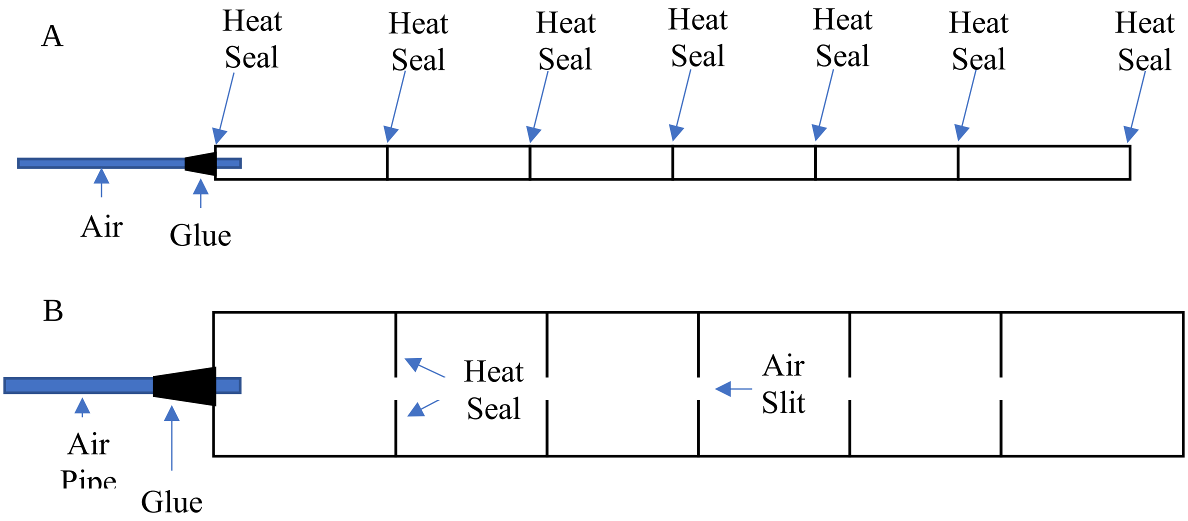
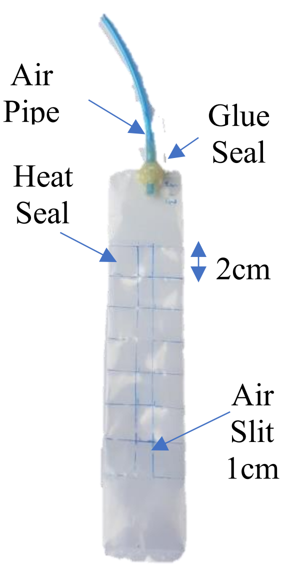
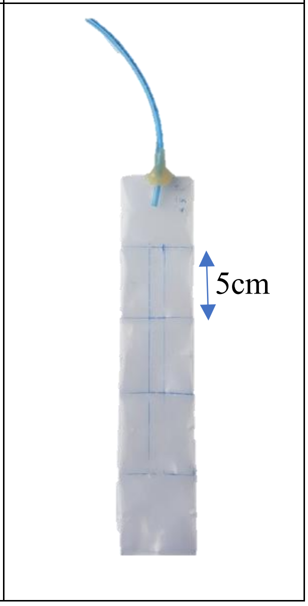


Figure 4.1. (A). Side profile of actuator design; (B) Top view of actuator design

4.3.1 Air Chambers

Actuators with different sized air chambers were created to assess how they would affect the performance. Each actuator had the same air slit size of 1cm in the middle of the polythene tubing. Different air chamber sizes of 2cm, 3cm, 4cm and 5cm were used. Each actuator had an air chamber size of 5cm at both the top and bottom of the actuator to allow for fixation. The actuators that were manufactured can be seen below in Table 4.1.

Table 4.1. The Different Air Chamber Designs

2cm	3cm	4cm	5cm
			

4.3.2 Air Slits

Actuators with different sized air slits were also manufactured to see if this would have an effect on the performance. Each actuator had the same air chamber size of 5cm. The actuators had different air slit sizes of 1cm, 1.2cm, 1.4cm, 1.6cm and 2cm, with them all being in the centre of the polythene tubing. The actuators that were manufactured can be seen in Table 4.2.

Table 4.2. The Different Air Slit Designs

1cm	1.2cm	1.4cm	1.6cm	2cm
				

4.4 Summary

To summarise, this chapter has discussed the manufacturing techniques of the different actuator designs. There are four actuators with different sized air chambers, and five with different sized air slits. These actuators will now be tested to understand the how the perform in static and dynamic tests. The next chapter will discuss the methods and results for the range of motion tests that the actuators underwent.

Chapter 5: Static Task

5.1 Introduction

Chapter 4 discussed the different actuators that were designed and manufactured. This chapter will present the methods used to test the range of motion of each of the actuators and to see how different air slit and air chamber sizes may impact the movement that is able to be achieved. This will assess which designs match the movement profile of the knee and fingers best and hence see which actuator would be best suited for use in an exosuit. The methods will be covered first, followed by the results, and then lastly there will be a discussion on the findings from the testing.

5.2 Methods

5.2.1 Testing Rig

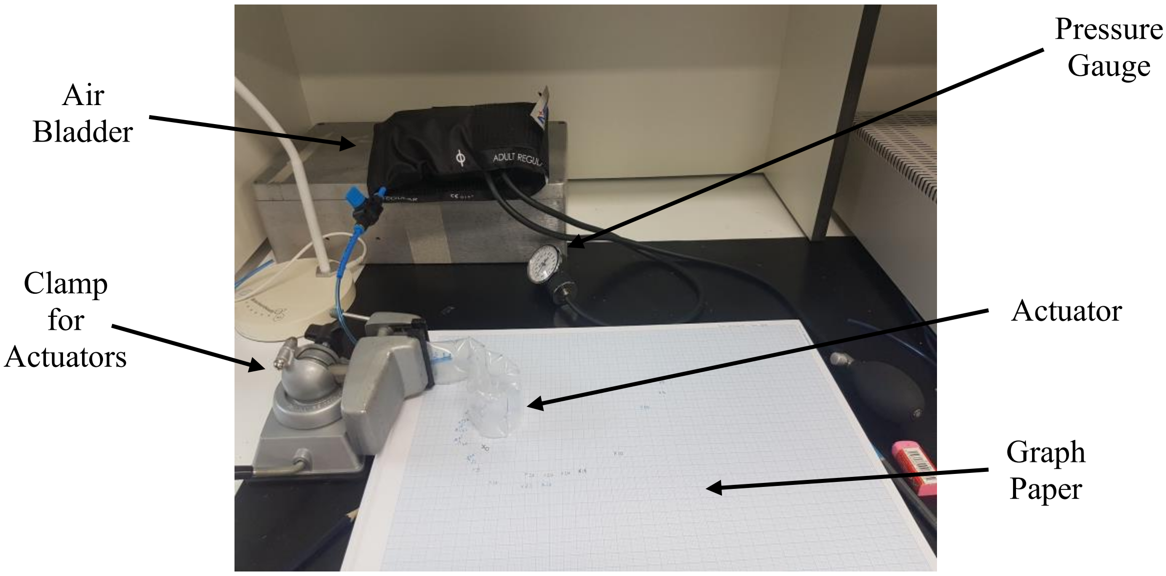


Figure 5.1. The testing rig used to assess the range of movement of the actuators during the static test

The range of movement during a static task for the four different air chamber sizes and five different air slit sizes was performed using the same testing set up which can be seen in Figure 5.1. The testing rig consisted of a sphygmomanometer that had been adapted. An additional air pipe was inserted into the air bag and glued in to ensure no leaks would occur. A valve was then attached to this pipe so that the airflow could be controlled in and out of the air bag. The airpipe was then attached to the actuators so that air could flow into them. The pressure gauge on the sphygmomanometer was used to measure the air pressure that was in the actuators at certain points. Each actuator was clamped perpendicular to the graph paper that was flat on the table and perpendicular to the clamp. The graph paper was marked with the starting position of the tip of the actuator. The tip was defined as the point at the end of the actuator that was touching the graph paper. The hand pump was used to pump air into the actuators. At every 5mmHg, the graph paper was marked to show how the tip of the actuator had moved. This was repeated until no further movement of the actuator occurred. Each actuator was tested on three occasions to improve reliability of results and to get an average of the range of movement achieved. This was done for all of the actuators with a new piece of graph paper used for each of the different actuators.

5.2.2 Data Processing

After the data had been collected for each of the actuators, axes were created on the graph paper so that the coordinates of the points could be found. The coordinates for each test from the different actuators were then put into Excel where the averages for each pressure were determined. As the distance and angle of movement is of interest in this study, the cartesian coordinates were converted into polar coordinates using MATLAB (ver. R2018b, MathWorks, Massachusetts, US). The function of: [t,r] = cart2pol(x,y) was used to undertake this. From this, the graphs were then able to be formed to compare how different actuators performed during the range of movement test.

5.2.3 Data Analysis

In order to understand the relationship between the angle and distance moved for each of the actuators, least squares regression was undertaken to estimate the equations of the lines. The following equations were used:

$$r = ae^{b\theta} \tag{1}$$

By taking the natural log of both sides yields:

$$\ln r = \ln(a) + \ln(e^{b\theta}) \tag{2}$$

$$\ln r = \ln(a) + b\theta. \tag{3}$$

Let:

$$z = \ln r;\ a_0 = \ln(a);\ a_1 = b \tag{4}$$

Therefore:

$$z = a_0 + a_1\theta \text{ (linear model)} \tag{5}$$

The linear model regression formulas could then be used:

$$a_1 = \frac{n\sum_{i=1}^{n}\theta_i z_i - \sum_{i=1}^{n}\theta_i \sum_{i=1}^{n} z_i}{n\sum_{i=1}^{n}\theta_i^2 - \left(\sum_{i=1}^{n}\theta_i\right)^2} \tag{6}$$

$$a_0 = z - a_1\,\theta \tag{7}$$

Once the two unknows were calculated, they were substituted into the original constants, where:

$$b = a_1. \tag{8}$$

$$a = e^{a_0} \tag{9}$$

5.3 Results

For each of the actuators that had been designed, a static test was conducted to understand the movement capabilities of each design. The results from this test would aid in giving a better understanding of the optimal design to aid in flexion of the knee and finger. The results for the different sized air chamber and air slits will now be presented.

5.3.1 Air Chamber Results

The photos below in Figure 5.2 show an example of the movement progression of one of the actuators as the pressure increases. The photos show the 3cm air chamber actuator and suggest that this actuator has a good range of movement and successfully curls back on itself which resembles a similar movement pattern to that of the human finger.

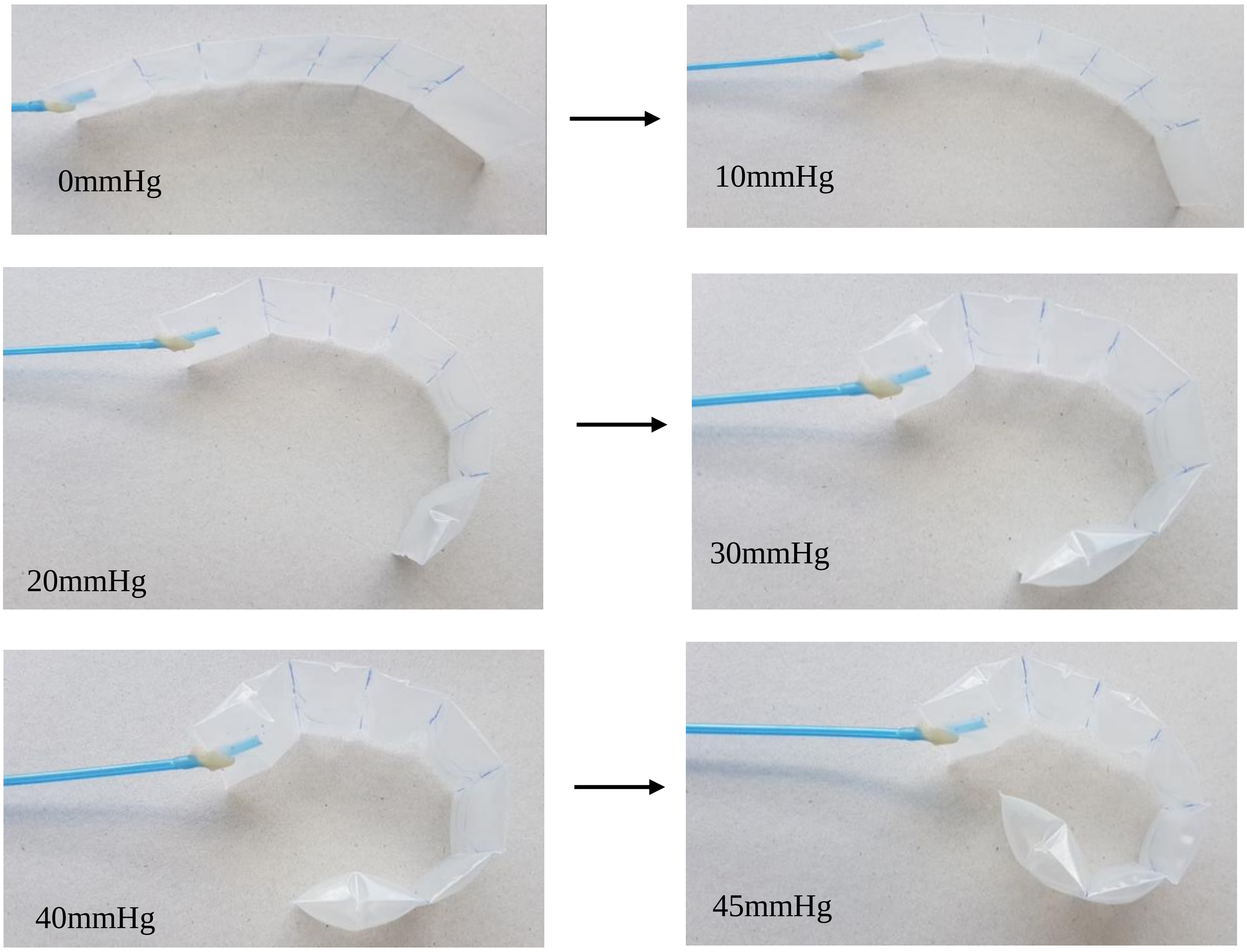


Figure 5.2. 3cm Air Chamber Actuator at Different Pressures

The results of the testing were gathered, and the static test results can be seen below in Figure 5.3. The graph depicts the movement of the tip of the actuator and each point refers to an increase of 5mmHg. All of the actuators average results were plotted on the same graph to allow for direct comparison of the movements achieved by each air chamber size.

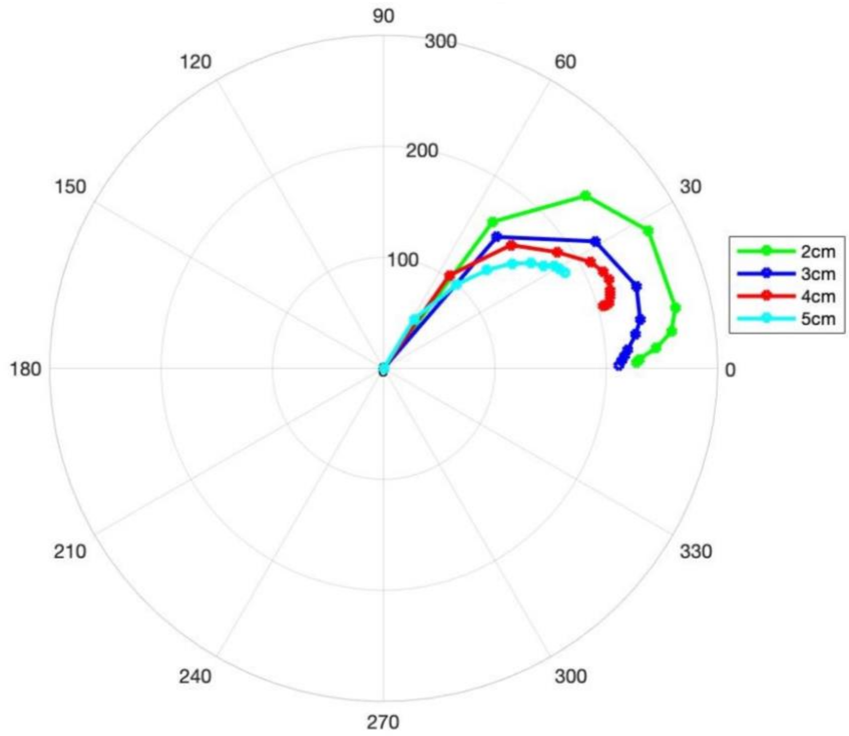


Figure 5.3. Impact of Air Chamber Size on the Range of Movement Obtained

The results would suggest that the 2cm sized air chambers allowed for the greatest range of movement with the 3cm sized air chambers also demonstrating a good range of movement. Both of these actuators managed to fully curl up on themselves and both had an approximate range of movement of 60°. The 3cm and 4cm sized air chambers displayed less movement with neither being able to fully curl up and displayed about 30° range of movement. The actuators with 2cm air chambers required 40mmHg for full movement. Both the 3cm and 5cm air chamber actuators required 45mmHg and the 4cm air chamber required 55mmHg until full movement had been achieved.

After using least squares regression, the equation of the lines for the air chamber actuators are estimated as follows:

$$\text{2cm: } r = 87.13e^{1.35\theta}$$

$$\text{3cm: } r = 92.31e^{1.39\theta}$$

$$\text{4cm: } r = 123e^{7.96x10^{-3}\theta}$$

$$\text{5cm: } r = 9.25e^{3.63\theta}$$

5.3.2 Air Slit Results

Tests were also undertaken to see how air slit size may impact the range of movement achieved by the actuators. The results from the testing can be seen below in Figure 5.4. Again, the graph depicts the movement of the tip in intervals of 5mmHg. Again, all of the actuators average results were plotted on the same graph to allow for direct comparison of the movements achieved by each air slit size.

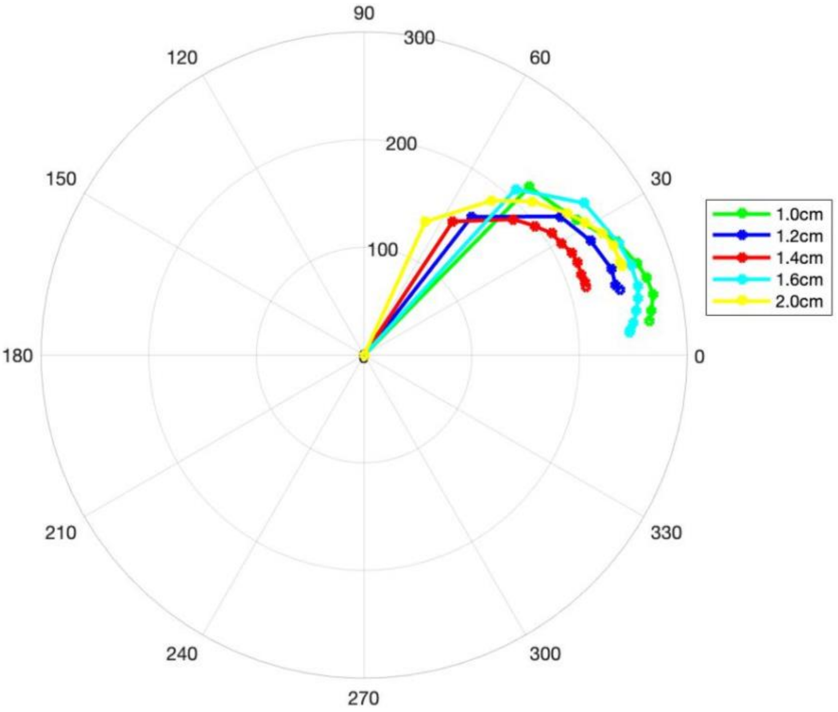


Figure 5.4. Impact of Air Slit Size on the Range of Movement Obtained

The results from this testing would suggest that changes in air slit size does not impact the range of movement greatly as there appears to be no trend in whether a smaller or larger air slit size improves the movement able to be achieved by the actuator. All of the different actuators follow a very similar line of movement with a similar angle being achieved for all of them. The 1cm air slit required 40mmHg for maximum movement, the 1.2cm required 30mmHg, the 1.4cm and 1.6cm air slits required 50mmHg, and lastly, the 2cm air slit required 45mmHg for full movement to be achieved.

After using least squares regression, the equation of the lines for the air slit actuators are estimated as follows:

$$1.0\text{cm: } r = 47.98e^{3.36\theta}$$

$$1.2\text{cm: } r = 20.53e^{3.95\theta}$$

$$1.4\text{cm: } r = 22.68e^{3.53\theta}$$

$$1.6\text{cm: } r = 79.87e^{2.30\theta}$$

$$2.0\text{cm: } r = 28.36e^{2.75\theta}$$

5.4 Discussion

The results of the static test on the different actuators would suggest that the smaller the air chamber size the greater the range of movement that is able to be achieved. This could be due to an increase in the number of seals in the actuator which promote and allow for greater bending movement to occur. These results suggest similar patterns to what the finite element analysis found, where the smaller air chambers had greater displacement than the larger air chambers. The estimated equations of the lines that were calculated also suggest that greater movement will be achieved at different angles for the smaller air chamber actuators. However, due to the increased number of seals on the smaller air chamber actuators there was an increase in failure rate. The finite element analysis suggested that around the heat seals there would be higher levels of stresses and strains place upon them and this is likely to be the cause of the bursting around these joints. The actuators managed to achieve approximately 60° of flexion which suggests that they have a similar flexion range to that of a human finger.

The results for the air slit actuators suggest that air slit size does not affect the ranges of movements as greatly as air chamber size does. The finite element analysis suggested that similar movements would be achieved during lower pressures, but the smaller air slit sizes would yield better results in term of movements at higher pressures. This does correlate with the results in this test to some extent, with the actuators having almost the same movement pattern to a point but then the 1cm air slit produced the largest movement range. The largest air slit size actuator of 2cm yielded the poorest angle, this could partly be due to the fact that less of the actuator was heat sealed on either side which meant less bending at the heat seals could be produced.

These results would suggest that in terms of range of movement, a smaller air chamber size would be best for range of movement. The 3cm air chamber actuator would be the choice based on these results as it had good movement range but less chance of failure than the 2cm air chamber actuator as the fewer heat seals meant that less stress was put on the seals. It should also be noted that the actuators did not require very high air pressure to become fully inflated. This would suggest that they would be safe for use in children as only low pressures are required.

5.5 Summary

In summary, this chapter has presented the results for the ranges of movement achieved by the different sized air chamber and air slit actuators. It was found that air slit size did not have a significant impact on the range of movements achieved. However, the air chamber size did contribute to differences with the smaller air chamber size of 2cm yielding the greatest range of movement out of the actuators tested.

The next chapter will present the dynamic task where the same actuators were tested to see how they would react with loads, and whether the movements achieved would still be similar to that of the static test.

Chapter 6: Dynamic Task

6.1 Introduction

In the previous chapter we saw how air chamber size and air slit size impacted the range of movement of the actuators in a static task. This chapter will present the methods used to test the range of movement during a dynamic task and to see how the results from the static task compare to the dynamic task and to also understand the capabilities of the actuators in terms of providing support to the knee and fingers. Firstly, the methods will be covered, then the results will be presented followed by a discussion on the findings which will conclude this chapter.

6.2 Methods

6.2.1 Testing Rig

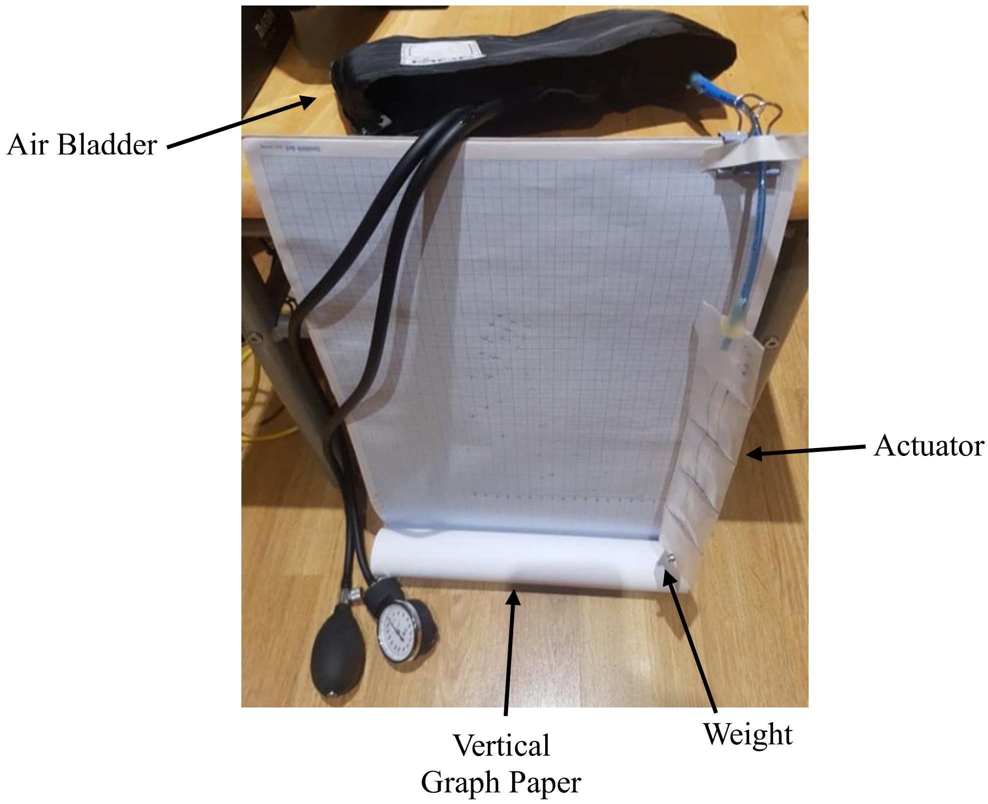


Figure 6.1. The testing rig used to assess the range of movement of the actuators during a dynamic task

To test the range of movemnt during a dynamic test, the testing rig that can been in Figure 6.1 was used. For the dynamic test, only the different sized air chamber actuators were used as the air slit had very little significance on the capabilities of the actuators. The same adapted sphygmomanometer was used as in the static test. For the dynamic test, the graph paper was positioned vertically with the actuator hanging down perpendicular to the graph paper. Different sized calibration weights of 1g, 2g and 5g were attached to the bottom of the actuators for testing. The graph paper was marked with the starting point of the tip of the actuator and air was then pumped into the actuator. At every 5mmHg the new point was marked to see the movement pattern of the actuator. Testing was stopped when the actuator moved no further. The actuators were tested three times with 1g of load, 2g of load and 5g of load in order to get averages for each of the weights used.

6.2.2 Data Processing

After the tests had been undertaken, axes were created on the graph paper to find the coordinates of each point. These points were then inserted into Excel where the averages were found for each of the weights for each actuator. These coordinates were then converted into polar coordinates so the angles of the movements could be determined. These points were then plotted on graphs so that the results for each actuator at different weights could be compared.

6.3 Results

The results from the dynamic testing were plotted and can be seen in the following figures below. The different weights for each actuator have been plotted against each other for a direct comparison of how an increase in weight changes the range of movements obtained by each actuator. Graphs of each weight have also been plotted for direct comparisons between the different actuators at the same weight to understand which actuators perform best in the dynamic tasks. The graphs depict the movement of the tip of the actuator and each point refers to an increase of 5mmHg.

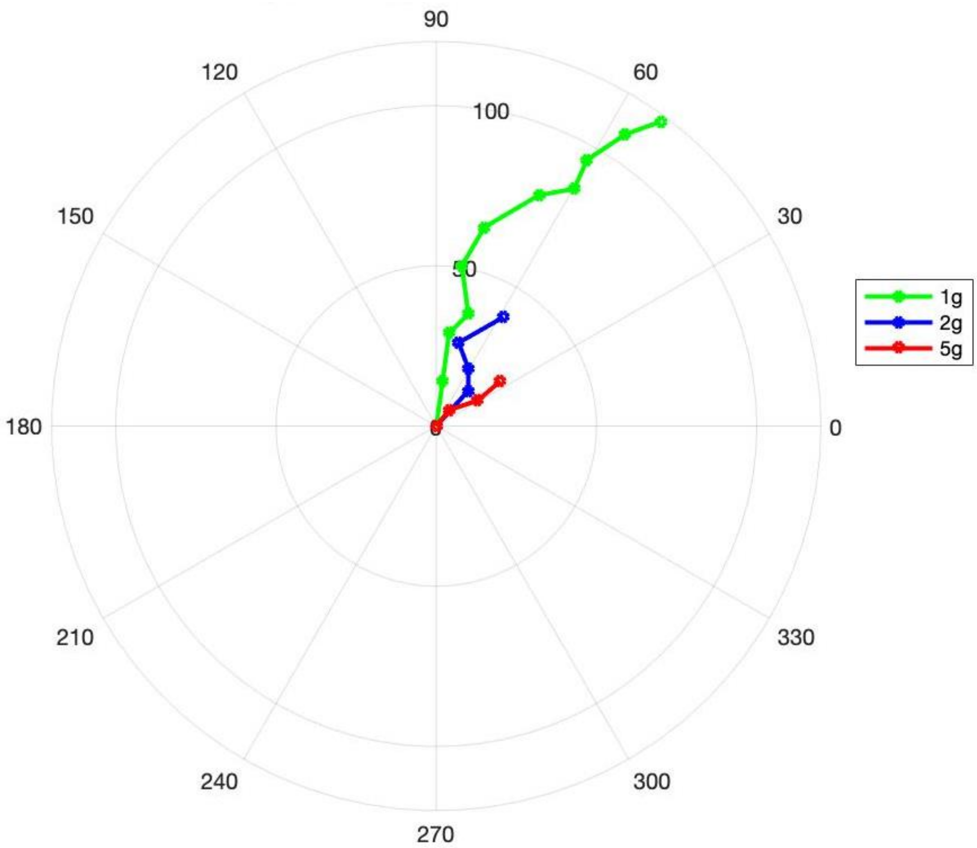


Figure 6.2. The Impact of Weight on 2cm Air Chambers

The results for the actuator with 2cm air chambers can be seen in Figure 6.2. These results would suggest that even with 1g of weight the same range of movement cannot be achieved as in the static task where the actuator was able to curl up on itself. It is clear to see that the increase in weight causes a massive decrease in movement able to be achieved by the actuator. With 5g of weight added, very little movement can be achieved by the actuator.

The equation of the lines for the 2cm air chambered actuators with weights are as follows:

$$1g: r = 4.17e^{2.06\theta}$$

$$2g: r = 1.23e^{2.77\theta}$$

$$5g: r = 1.78e^{2.66\theta}$$

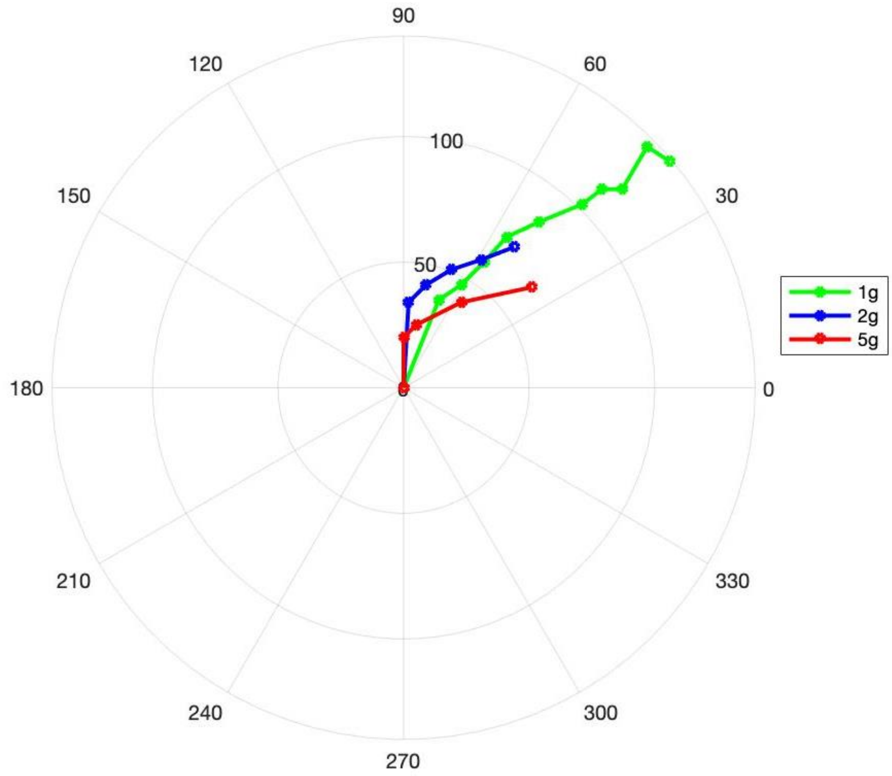


Figure 6.3. The Impact of Weight on 3cm Air Chambers

The results for the actuator with 3cm air chambers can be seen above in Figure 6.3. Once again, the increase in weight leads to a decrease in the range of movement achieved by the actuator and the curling effect of the actuator that was noted in the static test can no longer be seen.

The equation of the lines for the 3cm air chambered actuators with weights are as follows:

$$1g: r = 1.49e^{3.13\theta}$$

$$2g: r = 2.13e^{2.52\theta}$$

$$5g: r = 3.54e^{1.70\theta}$$

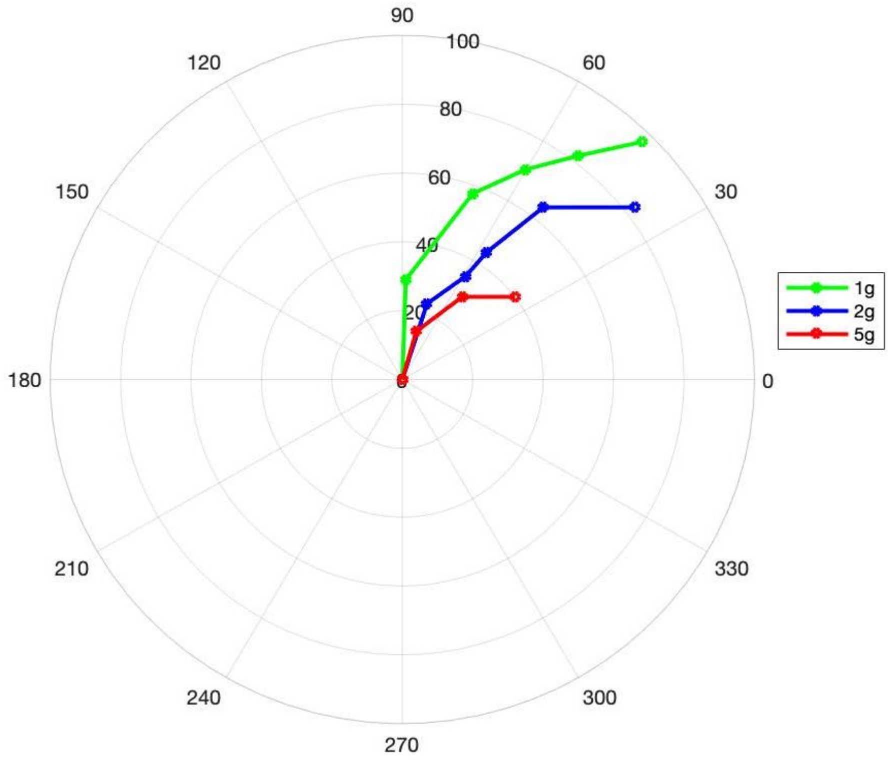


Figure 6.4. The Impact of Weight on 4cm Air Chambers

Figure 6.4 presents the results of the actuator with 4cm air chambers. This actuator has similar ranges of movement for both 1g and 2g of weight but with 5g of weight the range of movement is still limited. The movement also occurs more horizontally as opposed to vertically so no curling up affect occurs.

The equation of the lines for the 4cm air chambered actuators with weights are as follows:

$$1g: r = 2.94e^{1.17\theta}$$

$$2g: r = 2.69e^{2.71\theta}$$

$$5g: r = 2.30e^{2.23\theta}$$

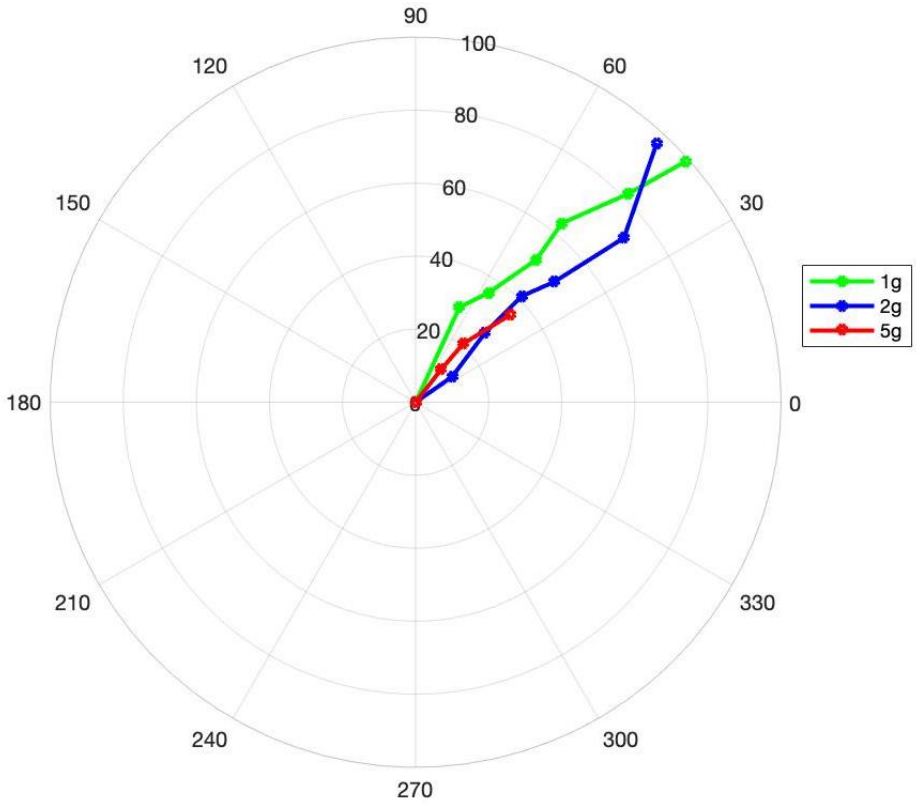


Figure 6.5. The Impact of Weight on 5cm Air Chambers

The final actuator to be tested was the actuator with 5cm air chambers and the results can be seen above in Figure 6.5. This actuator had extremely similar ranges of movement for both the 1g and 2g testing but again the movement was limited once 5g was added to the actuator.

The equation of the lines for the 5cm air chambered actuators with weights are as follows:

$$1g: r = 2.22e^{3.42\theta}$$

$$2g: r = 1.06e^{4.99\theta}$$

$$5g: r = 1.15e^{3.34\theta}$$

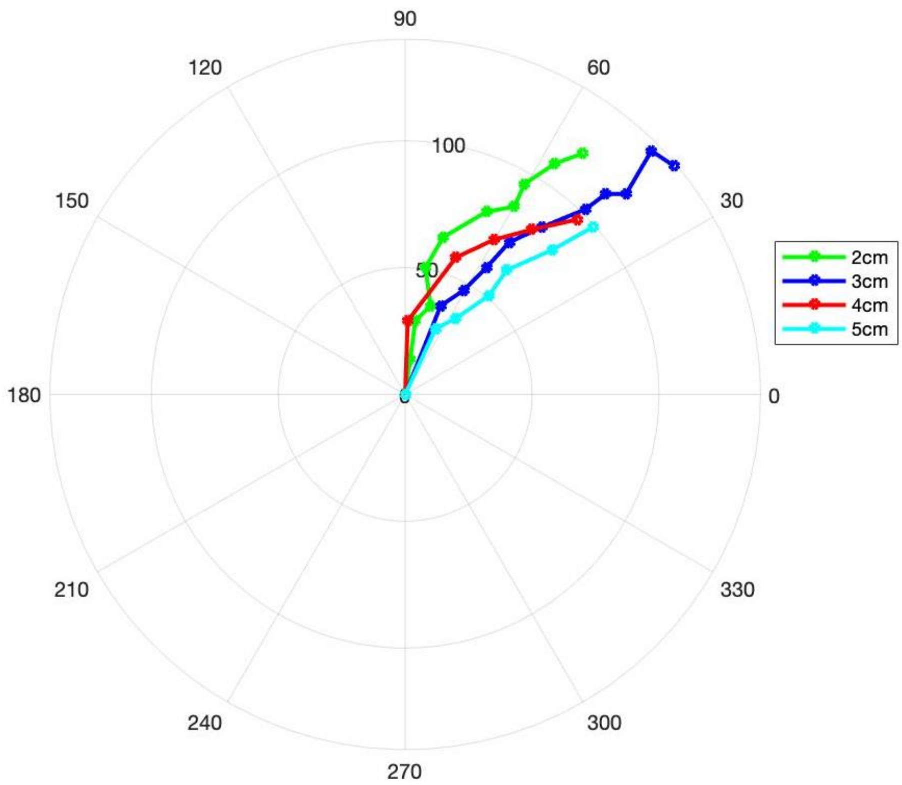


Figure 6.6. The Impact of 1g on Different Air Chambers

Figure 6.6 presents all of the actuators results when 1g of weight was added. The results suggest that the actuators with air chamber sizes of 2cm and 3cm have the greatest range of movement which is the same as what was suggested by the static results. Both the actuators with 2cm and 3cm air chambers required 50mmHg for full movement, with both the 4cm and 5cm requiring less with them needing 25mmHg and 30mmHg respectively.

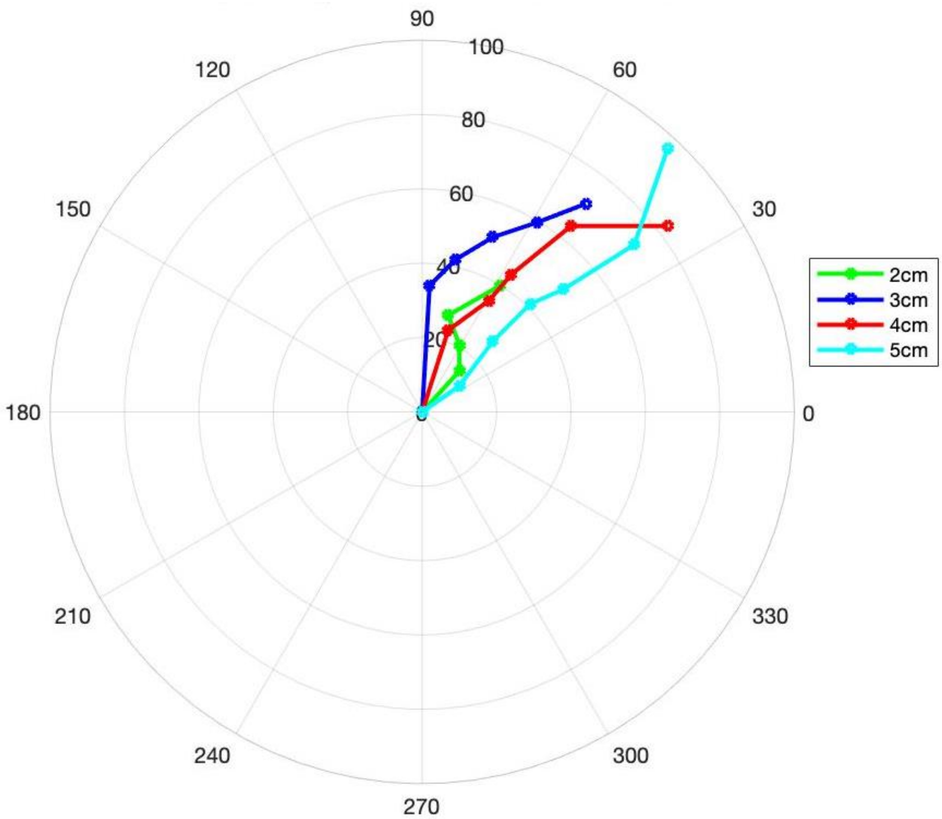


Figure 6.7. The Impact of 2g on Different Air Chambers

The results of the different actuators when 2g of weight was added can be found above in Figure 6.7. These results suggest that the 5cm actuator had the greatest range of movement when 2g of weight was added. However, both the 3cm and 4cm actuators have a more desired range of movement as they still curl inwards slightly which is more similar to the movement profile of the finger and knee. The actuator with 2cm air chambers required the least amount of pressure before maximum movement with only 20mmHg needed. Both the 3cm and 4cm air chambers required 25mmHg and the 5cm air chambers required 30mmHg for full movement to be reached.

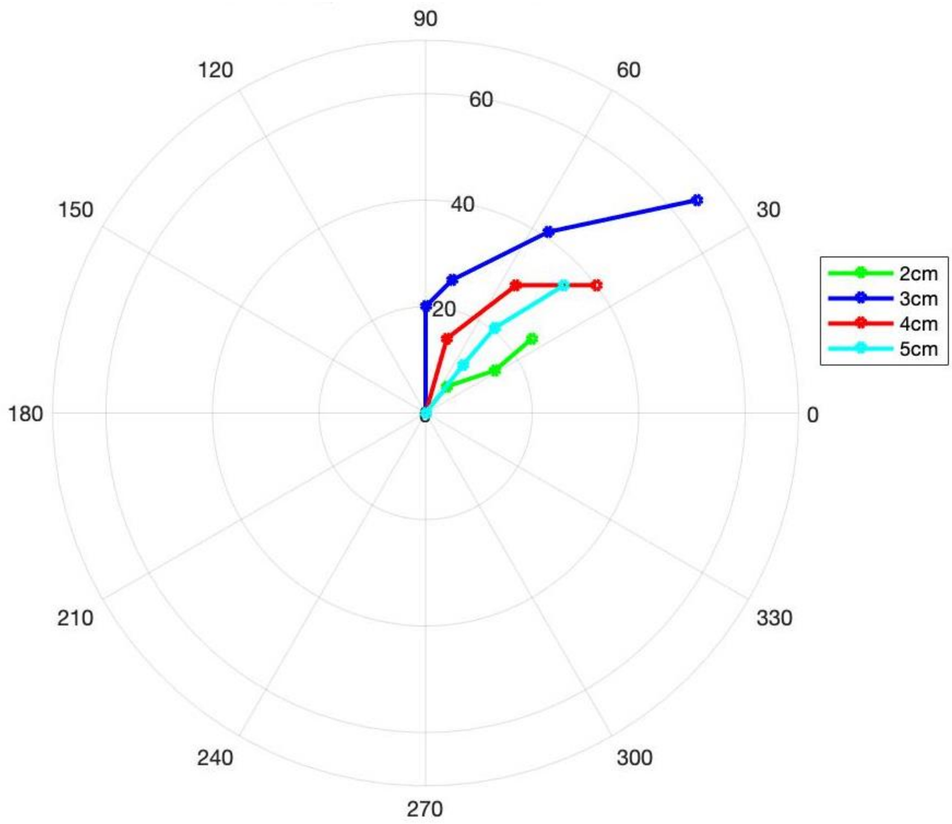


Figure 6.8. The Impact of 5g on Different Air Chambers

The final graph in Figure 6.8 shows the results of the heaviest weight used. The 2cm air chamber actuator has very little movement and struggles to move when 5g has been added. The 3cm air chamber actuator demonstrates the greatest range of movement and also produced a good curvature suggesting that this actuator can cope with heavier weights better than the other actuators. Due to these actuators moving less, the pressures required for maximum movement were lower than in the other tests. The 2cm, 4cm and 5cm air chambers only required 15mmHg before they could no longer move. The actuator with 3cm air chambers required 20mmHg until maximum movement was reached.

6.4 Discussion

The results from the dynamic testing suggest that the actuators are not particularly strong and struggle to move weights and go against the force of gravity. Straight actuators have been shown to be quite strong (58,59), but by creating air chambers it weakens the actuator resulting in poor performance results. The 2cm air chamber actuators have the worst results in this test with only a very limited range of movement being achieved with all of the weights. This is because of the increased number of air chambers. The larger chambers have better results with more motion being achieved. The fewer the air chambers the stronger the actuators will be. However, all of the actuators are always at least 30° away from the maximum flexion that a finger could obtain and all of them had reduced movement the heavier the weight got. This would suggest that these actuators would not be suitable for aiding in the movement of the finger and the material would need to be revised to make the actuators strong enough to provide some support to the finger or knee.

6.5 Summary

To summarise, this chapter has explored the methods and results of a dynamic task on the performance outcomes of the actuators. It was found that the increasing weight that was added to the actuators caused a decrease in the movements that could be achieved. The actuators struggled to perform the desired movements that would be required to aid in supporting finger or knee movement. The best actuator was found to be the actuator with 3cm air chambers as this had the greatest amount of movement and also curled slightly which is the desired movement to match the profile of the finger and knee.

Chapter 7 will now discuss the control system that was implemented in order to control the movement of the actuators.

Chapter 7: Control System

7.1 Introduction

The previous chapter looked at how adding weights to the actuators affected the range of movement that was able to be achieved. This chapter will look at the design of the control system and the methods used to control the actuators. First, the equipment that was used will be explained, then the design of the actuator that was used for testing the control system will presented. The code that was used to control the system will then be discussed and then lastly, the outcomes of what was able to be achieved.

7.2 Equipment

In order to make the control system, the following equipment was required:

- Fisherbrand FB70155 Pump (Fisherscientific, UK)
- Tenma 72-7245 Laboratory DC Power Supply (Premier Farnell, UK)
- Festo MHA2-MS1H-5/2-2-K Valves (Festo, Hauppauge, NY)
- Arduino Uno (Ivrea Interaction Design Institute, Italy)
- LED
- Resistors
- Solderless Board
- Relays
- Flex Sensor

7.3 Control System Design

The diagram below in Figure 7.1 presents how all the equipment was put together to form the completed control system with Figure 7.2 showing the actual system used.

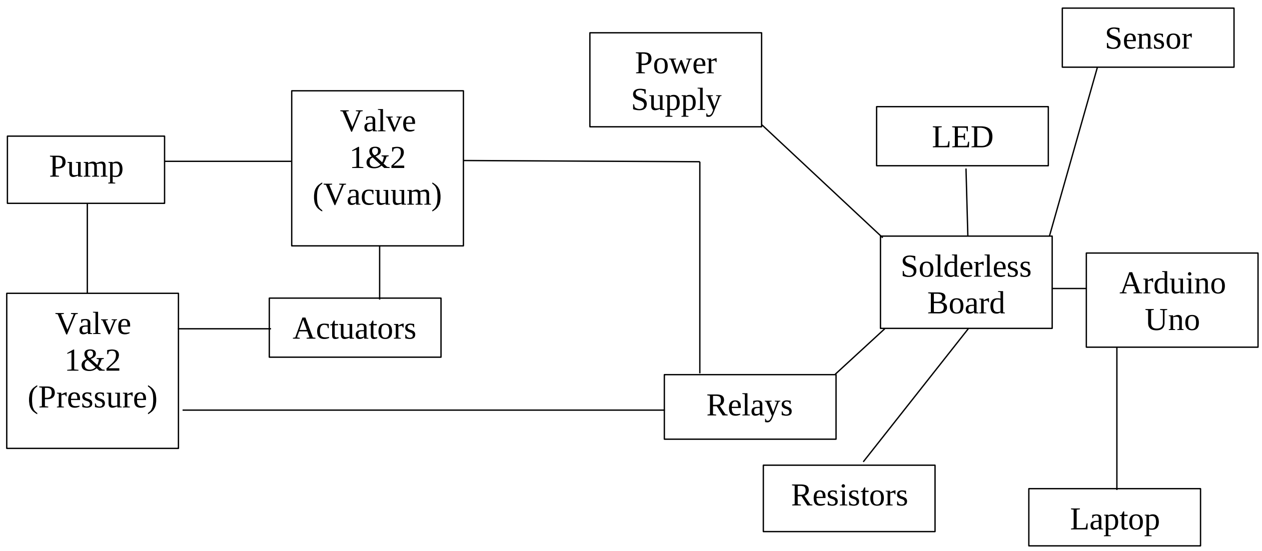


Figure 7.1. Flow diagram of the control system set-up

To reduce the weight of the design the pneumatic system was stowed in an off-board set-up. The pump was attached to four different valves. Two pumps acted as pressurisers to inflate the actuators, whilst the other two were vacuums to deflate the actuators. The solderless board contained the resistors, relays and the flex sensor. The Arduino was also attached to the solderless board to control the whole system. LEDs were used to signify which valve was on at certain times. The power supply went directly to the solderless board and relays were used to connect the valves.

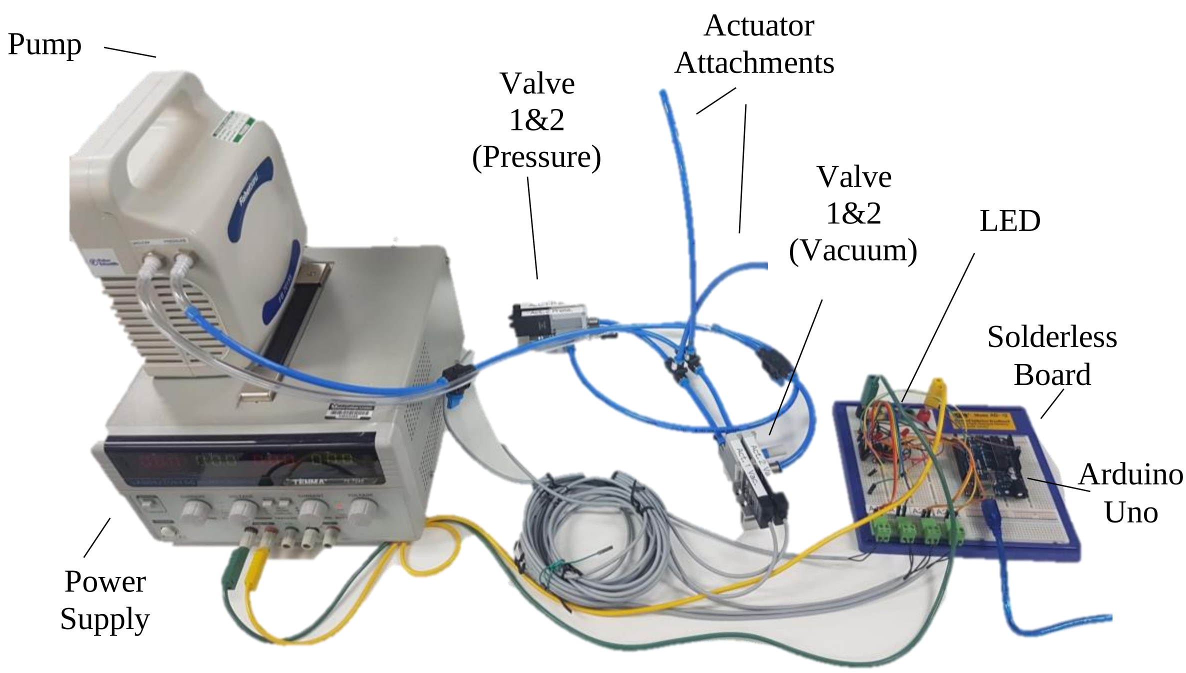


Figure 7.2. The actual control system setup

The photo seen below in Figure 7.3 shows how the flex sensor was incorporated into the solderless board. The flex sensor was used to control the air flow in and out the actuators.

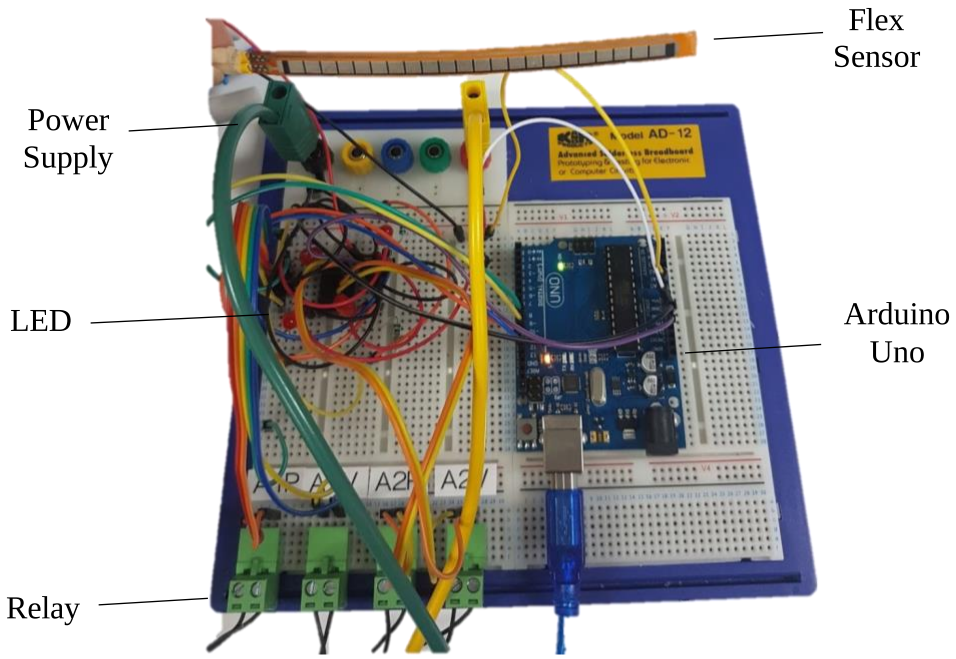


Figure 7.3. The solderless board showing the set-up and inclusion of flex sensor

7.4 Actuator Design

When testing the control system, a new actuator was designed so that flexion and extension could occur. The new actuator was formed of the same material but consisted of no individual air chambers and can be seen below in Figure 7.4. This actuator was designed to aid extension, whilst the air chambered actuators aided in flexion. By attaching the two together, and inflating/deflating at alternating times, it allowed for a full range of movement which more closely matches that of the finger and knee.

Figure 7.4. The straight balloon actuator

7.5 Methods

In order to control the system, the code, as seen in Figure 7.5, was developed.

```
//L293D
//Actuator 1
const int Act1PressSolenoid  = 9;  // Pin 14 of L293D
const int Act1VacSolenoid  = 10;  // Pin 10 of L293D
//Actuator 2
const int Act2PressSolenoid  = 11; // Pin  7 of L293D
const int Act2VacSolenoid  = 12;  // Pin  2 of L293D
//Sensor
const int flexPin = A0;

int flexValue;
int flexValue_old;


//This will run only one time.
void setup(){

    Serial.begin(9600);

    //Set pins as outputs
    pinMode(Act1PressSolenoid, OUTPUT);
    pinMode(Act1VacSolenoid, OUTPUT);
    pinMode(Act2PressSolenoid, OUTPUT);
    pinMode(Act2VacSolenoid, OUTPUT);
}

  // code runs in loop
  void loop(){

      flexValue = analogRead(flexPin);
      Serial.print("sensor: ");
      Serial.println(flexValue);

//This section pumps air into Actuator 1
if(flexValue - flexValue_old <= -5)
{
digitalWrite(Act1PressSolenoid, HIGH);
digitalWrite(Act1VacSolenoid, LOW);
digitalWrite(Act2PressSolenoid, LOW);
digitalWrite(Act2VacSolenoid, HIGH);
}
//This section sucks air out of Actuator 1
else if(flexValue - flexValue_old >= 5)
{
digitalWrite(Act1PressSolenoid, LOW);
digitalWrite(Act1VacSolenoid, HIGH);
digitalWrite(Act2PressSolenoid, HIGH);
digitalWrite(Act2VacSolenoid, LOW);
}
// shut everything off
else
{
digitalWrite(Act1PressSolenoid, LOW);
digitalWrite(Act1VacSolenoid, LOW);
digitalWrite(Act2PressSolenoid, LOW);
digitalWrite(Act2VacSolenoid, LOW);
}

flexValue_old = flexValue;
delay(500);

}
```

Figure 7.5. The Arduino code to use the flex sensor to control the actuators movement

Air was pumped into the air chambered actuator when the sensor value was decreasing to allow for flexion of the actuator to being. By using the code ‘if(flexValue-flexValue_old <= -5)’ it allowed the sensor to recognise that an increase in flexion was beginning and by pumping air into the air chambered actuator and vacuuming out of the straight actuator it allows for the flexion motion to occur. Similarly, if the value was ‘+5’ as opposed to ‘-5’, it signified extension was occurring and air would be vacuumed out of the air chamber actuator and air pumped into the straight actuator allowing for extension to occur. If no movement was recorded, then the system was turned off to prevent any unwanted pressurising.

7.6 Results

A B

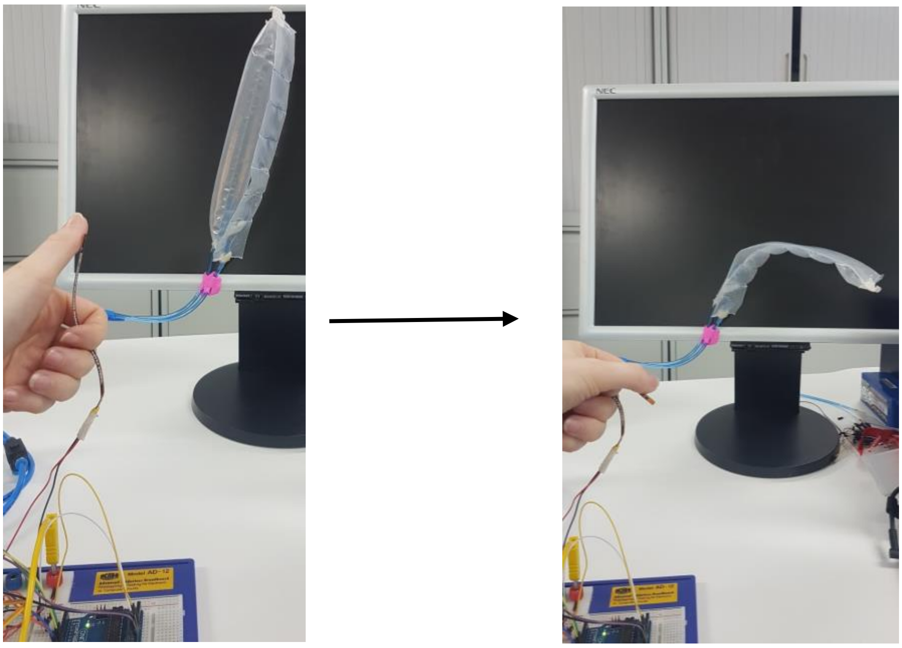


Figure 7.6. (A) Flex sensor straight causes extension; (B) Flex sensor bent causes flexion

The images above and below in Figure 7.6 and 7.7 show the resulting performance of the actuator when the flex sensor is used to regulate the air flow. It successfully shows that when the flex sensor is extending, the straight actuator is pressurised and produces extension. When the flex sensor is being bent, the air flow is pumped into the air chamber actuator causing flexion.

A B

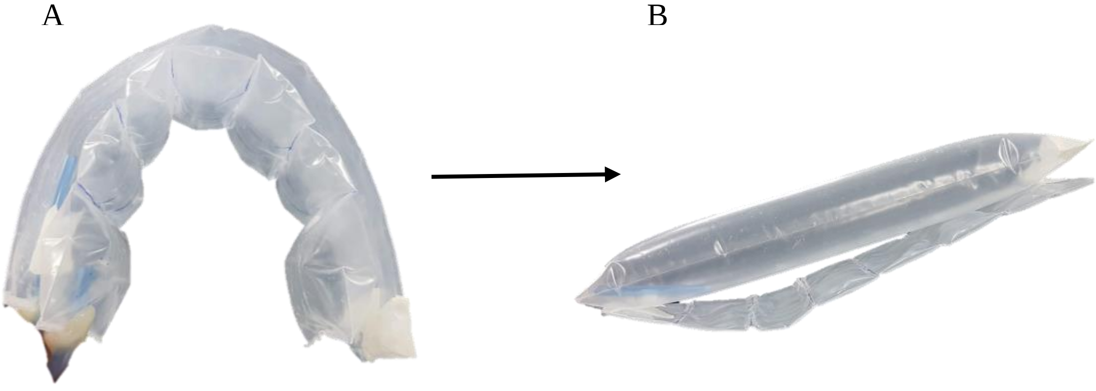


Figure 7.7. (A) Flexion of the actuator; (B) Extension of the actuator

7.7 Discussion

The described control system successfully enabled the flexion and extension of the actuator. The flex sensor enabled automatic pressurising and vacuuming at the appropriate times. The results suggest a good range of motion can be achieved using this control system and by having two-way movement it would allow for the fingers or knee to be aided during all tasks. However, the control is bulky and by no means portable. It has been suggested that soft exosuits need to be less than 500g in order to be usable in aiding daily living tasks(53). This control system is much heavier than this so would only be suitable as an offboard setting and to be used in rehabilitation instead for helping in everyday tasks. Also, the actuators do not bend as fully when using the control system as they did when being manually pumped, so greater air pressure and quicker pressurising speed would be required. The flex sensor would also need to be incorporated into the actuator so that the bending of the actuator results in pressurising and vacuuming at the correct times.

7.8 Summary

In summary, the control system successfully allowed for flexion and extension of the actuator. By incorporating a straight balloon, it allowed for the starting position of the air chamber actuator to be regained and also aid in extension. The flex sensor enabled automatic pressurising to occur.

The next chapter will discuss the applications of where this actuator design could be used.

Chapter 8: Applications

8.1 Introduction

This study has presented a novel actuator design that could be implemented into different applications for rehabilitative use to aid in extension and flexion of the joints. This chapter will present the different applications that this design could be used for.

8.2 Finger

Through appropriate scaling of the actuators, they could be implemented into a device for the finger to aid in flexion and extension. By incorporating the air chambered actuator on the top of the finger in line with the finger segments, downward forces could be applied, as seen in Figure 8.1, to encourage flexion of the finger. By using the straight actuator at the bottom of the finger, this could aid extension. Also, by incorporating a flex sensor into the design, the pneumatic system could work automatically and assist when the user wants to achieve essential daily tasks such as picking up objects. Through a similar technique as seen in the previous chapter, where air is pumped into one actuator and vacuumed out of the other, assisting the movement of the finger should be able to occur.

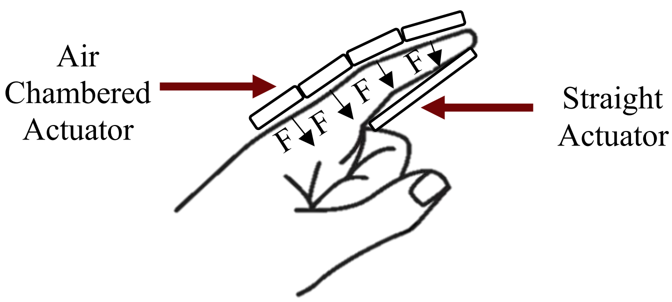


Figure 8.1. An example of how the device could be used on the finger

8.3 Knee

Another application where this actuator design could be used is in aiding the knee during ambulation. Through the use of stronger materials, the actuator would be able to provide some support to the knee. Again, through the use of both the air chamber actuator and straight actuator, aid could be given during both flexion and extension of the knee, providing vital support throughout the gait cycle as at present soft actuators only aid in the extension part of the gait cycle.

8.4 Other Age Groups

This device was primarily designed with young children in mind. However, this actuator would also be suitable for the elderly who have weak and fragile limbs and need some added support to help undertake motor movements. Due to the lightweight nature of the design it would not cause any harm to the user and could be implemented within care homes so that therapy can be undertaken to help strengthen their limbs, in particular their hands which become weak as they get older. This would allow them to regain some independence and carry out basic motor movements.

8.5 Summary

To summarise this chapter, this actuator has many applications that it could be used for. By incorporating both extension and flexion it allows for greater ranges of movements to be aided which currently most exosuits cannot provide. Through scaling of the device and use of stronger materials, it could be a useful for achieving movement and aiding in daily activities.

The next chapter will discuss the findings of this study and present the limitations and future work.

Chapter 9: Discussion

9.1 Discussion

This study aimed to create a soft-inflatable actuator for children who have cerebral palsy, and this was partially achieved. The actuator that was designed was extremely lightweight with each one weighing only 6g and they are also extremely flexible when not in use so would not obstruct a user in any way. As only small pressures were required to inflate the actuators, they are also safe for children with no dangerous forces being applied. The actuators are also cheap and easy to manufacture. When tested with the control system, flexion and extension did occur and had a similar profile to that of the finger or knee. The static results suggested that that smaller air chamber size and smaller air slit size would be best for achieving the greatest ranges of movement. However, the actuators were not robust enough and could not successfully move when external forces were added due to air chamber design weakening the actuators. Different materials would need to be looked into, or fibre reinforcement of the pre-existing air chambers in order to improve their strength and their capabilities of movement when external forces are applied such as a finger. With improvements to the materials used, the design should be able to be implemented into a hand or knee exosuit and provide a small percentage of aid to the user. The cheap and easy manufacturing methods of this design make it a promising actuator with good movement ranges being able to be achieved.

9.2 Limitations

There were some limitations involved with this study. Firstly, during testing of the actuators, some of the heat seals burst and air was released which could have affected the results for the movements that were achieved. Secondly, when the weights were attached to the actuators, they were stuck onto an air chamber. This could have restricted the pressurising of the air chamber which could have affected the motion of the actuator. In further studies the weight should hang from the actuator to stop this from occurring. Lastly, the end point of the actuator was determined by the human eye so some human error may have occurred when deciding where the end point of the actuator had moved to.

9.3 Future work

There is still further work that could be done to improve the outcomes of the actuator. Different materials need to be tested in order to understand which material will provide the greatest movement when external forces are added. It is important however, that the level of flexion that was found in the static testing is retained. Scaled down versions that would fit onto a child's hand should also be trialled to see if this has any effect of the movements that can be achieved. The actuators should also be trialled on human participants to understand if they are comfortable and also what degree of support they can provide to the user. The flex sensor also needs to be incorporated into the actuator to allow for automated control. Lastly, the control system needs to be made more compact so that this device could be used for daily tasks instead of just for rehabilitation.

Chapter 10: Conclusion

10.1 Concluding Remarks

To conclude, a successful concept for a novel soft-inflatable actuator has been designed. The lightweight and bending nature of the actuator make it a promising device for the future and with low costs could be suitable for growing children to use. With further research into stronger materials, this actuator could improve the quality of life of others whilst providing both flexion and extension which current pneumatic designs do not.

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