An investigation of using a silicone elastomer ethanol composite material for an arm rehabilitation device

Charlotta Mustonen

Examensarbete / Degree thesis
Materials Processing Technology (Swedish)
2020

EXAMENSARBETE	
Arcada	
Utbildningsprogram:	Process-och materialteknik
Identifikationsnummer:	20428
Författare:	Charlotta Mustonen
Arbetets namn:	En undersökning i att tillverka ett ställdon för armrehabilitering av silikongummi och etanol
Handledare (Arcada):	Stewart Makkonen-Craig
Uppdragsgivare:	Rasmus Björkvall

Sammandrag:

Mjuk robotik är en lovande gren inom robotiken. Till skillnad från hårda robotar, är mjuka robotar mer flexibla och de anpassar sig bättre till olika slags omgivningar. Deras elasticitetsmodul ligger nära de biologiska materialens så som muskel och skinn. De har därför möjligheten att fungera som en brygga mellan konventionella robotar och naturliga organismer. Mjuka robotar har väckt ett speciellt intresse inom den medicinska sektorn, där de har använts i olika biomedicinska applikationer så som mjuka instrument för kirurgi och ortoser för rehabilitering.

I detta arbete undersöktes möjligheten att relativt lätt och billigt tillverka ett ställdon av silikongummi och etanol som kan användas för rehabilitering av armen. Kompositmaterialet producerades av ett matrismaterial RTV-2 formsilikon 1520, och etanol ($\geq 95\%$) som användes som fasändringsmaterial. När etanol blandades och härdades med flytande silikongummi, bildades mikrobubblor över hela det komposita materialet. När materialet värmdes till 78,2 °C (som är fasändringstemperaturen för etanolen), började etanolen koka och det lokala lufttrycket började stiga inuti mikrobubblorna. När trycket steg inuti bubblorna, började materialet expanderas för att bli av med trycket. En prototyp av en produkt som kunde användas i rehabilitering av armen gjordes med hjälp av SolidWorks programmet. Efter det analyserades kompositmaterialets kompatibilitet med ställdonet, med förbättringsidéer för vidare forskning. På grund av COVID-19 pandemin och regeringens beslut att stänga skolan, kunde inte alla experiment slutföras.

Nyckelord:	Mjuk robotik, Rehabilitering, SolidWorks, Ställdon, Dimetylpolysiloxan, Kompositmaterial, Människa-robotinteraktion
Sidantal:	63
Språk:	Engelska
Datum för godkännande:	

DEGREE THESIS	
Arcada University of Applied Science	
Degree Programme:	Materials Processing Technology
Identification number:	20428
Author:	Charlotta Mustonen
Title:	An investigation of using a silicone elastomer ethanol composite material for an arm rehabilitation device
Supervisor (Arcada):	Stewart Makkonen-Craig
Commissioned by:	Rasmus Björkvall

Abstract:

Soft robotics is an emerging field of robotics, which uses materials that have a Young's modulus close to that of biological matter. In contrast to rigid robots, soft robotic materials are being used in applications where adaptability and flexibility are required. Studies have proven that soft robotic devices have successfully been used in rehabilitation purposes.

The aim of this thesis was to manufacture a relatively economical, easy, and safe actuator that could be used in the rehabilitation of a person with weakened arm motor function. The composite synthesized in this thesis was composed of a matrix material Addition Curing RTV-2 Mould Silicone 1520. Ethanol was added as phase change material and mixed and cured with the liquid silicone. In this process, ethanol vapours and air pockets are formed inside the material lowering the internal pressure to achieve equilibrium with the external pressure. When the material was heated to a temperature of 78,2 °C or higher the ethanol started to boil, and the pressure grew forcing the silicone elastomer to undergo an expansion to get rid of the excess pressure to achieve equilibrium. Proposition of a design that could be used for rehabilitation purposes was done and tested using SolidWorks. After this, an analysis of the compatibility of the composite material to the design and improvement ideas for further research was done. Due to the COVID-19 outbreak, and governments decision to close the school, the thesis experiments could not fully be finished.

Keywords:	Soft robotics, Rehabilitation, SolidWorks, Actuator, Polydimethylsiloxane, Composite materials, Human-Robot Interaction
Number of pages:	63
Language:	English
Date of acceptance:	

TABLE OF CONTENT

Abbreviations and Acronyms

COR	Center of Rotation
PCSA	Physiological Cross-Sectional Area
UTS	Ultimate Tensile Strength
PDMS	Polydimethylsiloxane
PAM	Pneumatic Artificial Muscle
AM	Additive Manufacturing
ABS	Acrylonitrile Butadiene Styrene
PLA	Polylactic Acid
DC	Direct Current
V	Voltages
A	Amperes
N	Newtons
BMI	Body Mass Index
FEM	Finite Element Method

Acknowledgements

I wish to show my gratitude to my thesis supervisor Stewart Makkonen-Craig, for all the guidance and support he has provided me throughout my thesis. I would also like to thank Edwin Mwasi, with whom I worked parallel with during this thesis, for all his support and collaboration especially during the experimental part of thesis.

Furthermore, I wish to acknowledge Arcada's healthcare department for their professional input and advices regarding the medical part of my thesis work. I would also like to recognize the invaluable assistance that all the professors, colleagues, and staff members of Arcada have provided me during my studies.

Finally, I wish to thank my family and friends for their continuous support throughout my studies.

1 INTRODUCTION

1.1 Background

Soft robotics is an emerging and promising field of robotics. Contrary to robots that are built from rigid materials, soft robots are more flexible and more adaptable to different surroundings. [1] In addition to this, soft robotics offers a safe and relatively inexpensive solution to rehabilitate therapy patients.

Bio-inspired, soft robots can be composed using soft elastomeric materials. The choice of material and material geometry plays a vital role in the end products. The dimensions and the hardness of the material are key factors in determining how much load the material can withstand. It also affects how the stress is distributed throughout the material and how it deforms in usage. Materials with different stiffnesses and multi-material integration can allow systems to support wide range of loading conditions and applications. [2]

1.2 Relevance of problem

There are several neurologic disorders that can debilitate the arm. Stroke is one of the most destructive neurological diseases, because it can cause physical damage and invalidity. World Health Organization has reported that 15 million people suffer from stroke worldwide each year and 5 million are permanently disabled. [3] According to the United Nations report “World Population Ageing” released in 2017, it is hypothesized that by the year 2050 there will be around 2,1 billion persons aged 60 or older. [4] These elderly people have a higher risk to suffer from some sort of disorders such as stroke and other injuries that can weaken their arm-motor function. [5]

Weakened arm-motor function can also be caused by a spinal cord injury, that causes temporary or permanent loss of sensory function or motor control of an arm or leg. Due to a high risk of developing secondary conditions such as deep vein thrombosis or pressure sores, it is important to provide the patient with immediate rehabilitation and care to prevent further conditions that can cause damage or be life threatening to the patient. Assistive technology is often needed to aid the patient with movability and self-care activities, promoting the patient's own independence meanwhile supporting the integration back into society. [6]

Arm-motor function is vital for performing everyday tasks. Therefore, arm rehabilitation is very important, and robotics have been proven to be a prosperous part of the rehabilitation process [7] Unfortunately, many of the current products available are expensive and difficult to use. Only 5-15% of people in low- and middle-income countries have access to the assistive devices they need. [6] For this reason, more affordable and accessible arm rehabilitation devices are needed.

1.3 Aim of thesis

The aim of this thesis is to study the possibility to produce a relatively low cost and easy method for an arm rehabilitation actuator.

This thesis represents a simple McKibben inspired design of an actuator done in 3D-design modelling software SolidWorks for an arm rehabilitation patient. Experiments were also planned to produce a soft composite material that would work as an actuator in a such device. The actuator design proposed in this thesis mimics the bicep-triceps movement from a resting position to a 90-degree position (agonist-antagonist movement). The actuation happens due to a rapid expansion of the material which is caused by the change in internal pressure. Previous studies and experiments have shown that phase change materials have been used successfully to make various soft robotic devices due to its unique properties enabling rapid volume change when the material reaches its phase change temperature. [8]

To address the issues above, the objectives of this thesis were to:

- Write a review of robotics ethics and safety, soft robotic materials and properties, mechanics of bicep-triceps movement, biomechanical problems of stroke patient, soft robotic devices that support arm movements and lastly design, manufacturing and testing of soft robotic devices
- Production of the composite material
- Proposition of a design that could be used for arm rehabilitation purposes using SolidWorks design program and perform a test simulation to the product
- Perform a tensile test to the specimen
- Analysing the compatibility of the composite material for the design
- Improvement ideas for further research

The theory behind the thesis work is presented in chapter 2. The chapter is divided in five main subsections, firstly an overview of the history of robotic devices and ethics are represented. The other subsections focus on soft robotic materials, design, current soft robotic devices, kinesiology of the bicep-triceps movement and biomechanical problems of stroke patients.

Chapter 3 is a review of the experimental part: the production of the composite material followed by the design process and testing of the product using SolidWorks. In chapter 4, the results of the experiment and the design are discussed and analyzed with improvement ideas for future research.

2 LITERATURE REVIEW

The purpose of the literature review is to provide an understanding of the history and theory behind soft robotic materials and devices. The literature review is divided into five-subsections, which represents the most important findings and studies related to soft robotics. The first sub-section, 2.1, uncovers the history and ethics of robotic devices. The second sub-section, 2.2, focuses on the material properties of soft robotic devices. Sub section 2.3 and 2.4 focuses on explaining the biomechanics behind the bicep triceps movement, including the biomechanical problems stroke patients have. Sections 2.5 and 2.6 will give the reader an overview of existing soft robotic devices available including designing and testing of such devices.

2.1 Robotic devices and ethics

2.1.1 History of robotic devices

The etymology of the word “robot” is quite new though the concept of robotic devices dates thousands of years back. The term robot is derived from the Chez word *robota*, meaning forced labor. [9] One of the earliest mechanical devices were constructed in ancient China (1023-957 BC) by a mechanical engineer called Yan Shi, who built a mechanical figure which could move and perform several human-like movements. [10]

In 15th century Europe, Italian engineer, and inventor Leonardo Da Vinci, designed and presumably built a robot that could wave its arm, move its head, and close its jaw among other things. This was discovered from his notebook that was re discovered in the 1950s by investigators at the University of California. [11]

We have come a long way in the field of robotic devices since then, mainly thanks to the advances in the field of electronics, complex mechanics, and chemistry. Robotics have become incorporated into our daily life, and it is hard to imagine a world without robotic technology.

2.1.2 Robotics ethics and safety

Since robotic devices are being used in tasks that require precision and reliability, it is important to think about the ethics and safety of robotics. Even though many of us would agree that robotic devices are helpful at the same time many are concerned about the impact of robotic technology in our society. This is partially due to how robots are being portrayed in our society and popular culture. In the history of science fiction, robots have often been dramatized and portrayed as evil and potentially dangerous. The advances in artificial intelligence has led to the automatization of many jobs. Robots can perform tasks that human are unable of, such as working in extreme surroundings and performing tasks that require absolute precision or repetition. A lot of humans are therefore worried about a future where robots and computers can perform many of the tasks that were earlier done by humans, resulting in a decrease for the need of human labor.

Since humans and robots share the same working environment, the study of collaborative robotics is more important now than ever, ensuring the safety of humans and improving the acceptance of robotics. The integration of robotics should be done in a way that benefits all humans, improving the general trust of the public whilst maximizing the potential of robotic devices in our society. Robots should not exist as our enemies, but rather as devices promoting our safety and general well-being.

Robotic devices are extensively used in many different fields, such as manufacturing, military, space exploration, healthcare such as surgery, rehabilitation, and therapy. Soft robotics offers a relatively safe method to produce healthcare assistive devices. Soft robotic devices can undergo large deformations and unlike traditional robots, provide dexterity and more degrees of freedom. These are qualities that are very desirable in the medical field. However, there are some issues that needs to be addressed when it comes to the safety of the soft robots. Firstly, due their lightweight, it is harder to control them. In repetitive tasks and tasks where absolute precision is needed rigid robots still outperforms soft robots. [13] Tasks like grasping, manipulation and locomotion can be improved by integrating sensors to the soft robotic device: force, humidity, and heat sensors can be used to collect data of the human body and local environment. [14]

Material failure is also a concern, since soft materials have poor tear resistance and behave in general more unpredictable compared to rigid robots. If a soft robotic device that is in close contact with a human, like a medical robot, suddenly fails, the results can be very devastating resulting in the release of unwanted elastic energy or pressure. Another thing that can cause material failure in soft robotic devices, is the Mullins effect. The Mullins effect is a phenomenon that is widely observed in soft robotic materials such as silicone rubber, which leads to strain softening that is irreversible. This is due to a breakage of the polymeric chains at microlevel. To combat material failure, more accurate mathematical models and finite element analysis could be introduced to identify possible ruptures and to set proper safety limits for the material. The usage of a flexible covering, like a braided sheet, could also decrease the material tearing and overall failure. [13]

2.2 Soft robotic material properties

The purpose of this subsection is to discuss the material properties of soft robotic devices.

Soft polymers in the form of a fluid, gel or a material that can undergo large strains are often used in soft robotic devices. [15] This can be helpful when performing tasks that require flexibility and adaptability.

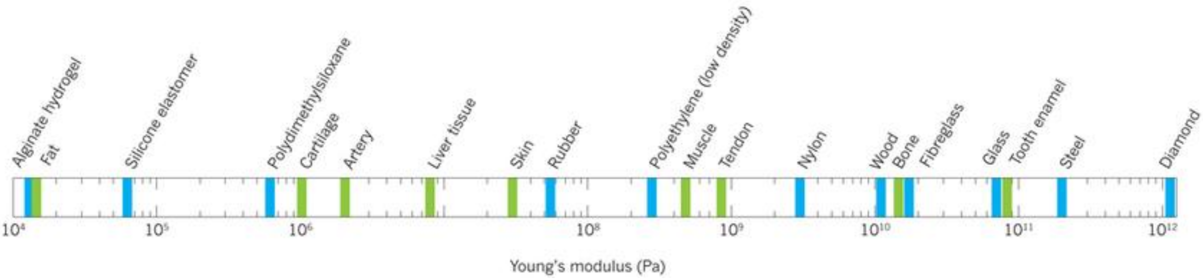


Figure 1: Young's Modulus of selected engineering materials [16]

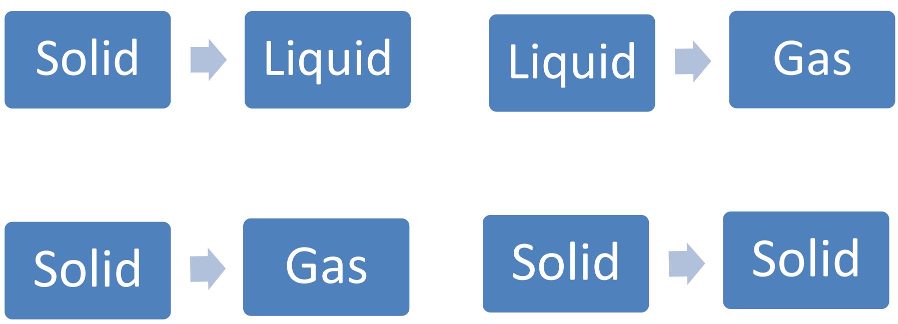
Soft robots are produced of materials that have a similar Young's Modulus to biological materials such as muscles and skin. Due to this, it is said that soft robots are mechanically capable of lifelike functions [15]. They have the possibility to work as a bridge between conventional machines and natural organisms. Soft robotic devices are especially interesting in different biomedical applications, such as providing soft tools for surgery, exoskeletons and prostheses, artificial organs and even in drug delivery. [16]

Soft robots are traditionally actuated pneumatically, hydraulically or by using electroactive polymers and shape memory polymers which require external stimuli such as a temperature change or stimulation by an electric field. More recently, composite phase change materials have been used in different soft robotic devices. [8]

2.2.1 Phase change materials

Phase change materials undergoes a phase change once it reaches its phase change temperature. During this phase change process, the material produces mechanical force which occurs due to a rapid expansion and the material either absorbs or releases heat.

The four types of phase changes are:



There are both organic and inorganic PCMs. Organic phase materials can be divided in two sub-categories: paraffins and non-paraffins. Inorganic phase change materials include salt hydrates, saline composites, and metallic alloys. [17] Phase change materials have conventionally been used in applications where energy storage is required. They have been used in many different fields, such as solar engineering, various spacecraft thermal applications and medical applications such as hot and cold therapies. [18] Phase change materials offers a lucrative alternative to conventional electromechanical actuators in soft robotics due to its low voltage requirement to undergo a rapid volume expansion. [8]

2.2.2 Polymer fluid composite material

Multi-material soft robots are being extensively studied due to their unique properties when it comes to functionality and actuation. 3D-printing technologies have evolved rapidly in recent years, enabling complex material and geometry integrations. Multi-material integration enables the design to perform complicated task whilst supporting the functionality of the soft robot. [19]

2.2.2.1 Silicone rubber

Silicone rubber is an elastomer, containing silicone, carbon, hydrogen, and oxygen. The combination of an inorganic backbone with organic groups attached to it, makes silicone rubbers in general very stable and non-reactive. Silicone rubbers can withstand a temperature of 150 °C without almost no changes in its properties. [20] Silicone rubbers also have a higher resistance to electromagnetic and particle radiation compared to organic plastics. They are widely used in the field of aviation, aerospace, and medicine where durability, flexibility, biocompatibility, extreme temperature, and radiation protection are needed. [20] Silicone rubbers are widely also used in soft robotic applications where it is important that the matrix material is flexible and adaptive to different surroundings. Additionally, the fabrication process of a silicone rubber actuator is in general quite easy and relatively cheap.

2.2.2.2 Ethanol

Ethanol is a widely used in different medical applications. Ethanol has been used in previous studies successfully as a phase change compound in soft robotic actuators, therefore it was chosen for this thesis project.

It is a colorless alcohol with a boiling temperature of 78,2 °C. Ethanol has the molecular formula:

CH_3CH_2OH [21]

When ethanol is mixed and cured with liquid silicone, the ethanol forms bubble-shaped pores throughout the silicone elastomer matrix. When the material is heated to a temperature of 78,2 °C or higher, the ethanol starts to boil, and the local pressure grows inside the bubbles. When the pressure grows, the silicone elastomer composite is forced to undergo an expansion to get rid of the pressure. [8]

2.2.3 Wetting of the material

Knowing the wettability of the material is very important. Contact angle measurement can be used to measure the wettability of a liquid on a solid surface. Wettability addresses how the liquid spreads on the surface. The wetting is measured by the contact angle which is formed when the liquid encounters the solid surface. [22] Surface roughness and surface chemistry are two fundamental things that influences the wettability of the material. Surface chemistry, which determines the surface energy and tension, has a major effect in how absorbing the material is. [22] When a liquid encounters the solid surface, a contact angle is formed. When the contact angle is smaller than 90 degrees, the material is hydrophilic, and wettability is good. Contrary, when contact angle is between 90-180 degrees the wettability is poor and the material is hydrophobic, meaning it repels the liquid. [23]

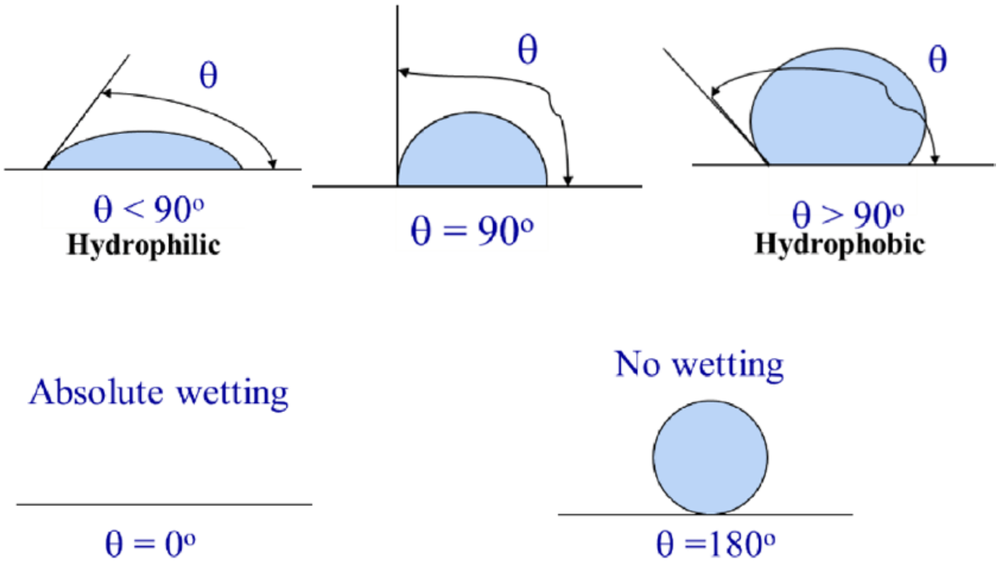


Figure 2: Contact angle [23]

In this thesis work, hydrophilicity was preferred since that allowed for the ethanol to spread properly and form microbubbles throughout the composite material, which is essential for the actuation. Previous studies states that ethanol and silicones are in general relatively compatible substances, and that wetting of ethanol on silicone is good. And therefore, suits this thesis experiment very good. [8]

2.2.4 Specific heat and electric actuation of the material

2.2.4.1 Specific heat, heat energy and power

The energy required to heat up a substance to a specific temperature, can be calculated with the following formula:

$$Q = mc\Delta T \quad [8]$$

where, Q is the heat energy (J), m the mass of a substance (kg), c the specific heat capacity ($J\ kg^{-1}\ K^{-1}$) and ΔT is the change in temperature (K).

A power source is needed to heat the material to a temperature of 78,2 °C or higher. Such power source could be e.g. a DC power device or a hot plate.

The power and time required to heat up the material using to a specific temperature can be calculated with the following formula:

$Q = \eta P t$ [8]

$P = VI$

$t = Q \eta P$

Where, η = efficiency of the heater, P = heating power (Watts, W), V = voltage (V) and I = current (Amps).

2.2.5 Stress, strain, and Young's Modulus

The strength of the material is one of the most important properties in a material. It determines how the material will perform, will it fail or not under pressure. Knowing how much load a structure can take before failing is utterly important for us. To prevent failures, engineers usually perform a structural analysis to determine how much force can be applied to the design before it breaks.

To determine how strong a material is, we must understand what stress and strain is in a material. Stress can be given as normal stress or shear stress, depending if the force given is parallel or perpendicular to the area.

Tensile or compressive stress, are referred to as normal stress (perpendicular stress) and can be calculated with the formula:

$\sigma = F / A$ [27]

Where,

σ = normal stress (Pascal, N/m^2)

F_n = normal force acting perpendicular to the area (N)

A = area (m^2)

Shear stress (parallel stress) can be expressed as:

τ = F / A [27]

Where,

τ = shear stress (Pascal, N/m^2)

F_p = shear force in the plane of the area (N)

A = area (m^2)

The maximum stress, which is called the ultimate tensile strength, is the maximum stress the material can withstand without breaking. The ultimate tensile strength can be determined by the following formula:

UTS = maximum load (Newtons) / area of original cross section (m^2) [27]

Strain (deformation) can be calculated using the following formula:

ε = dl / lo [27]

= σ / E

Where,

dl = change of length (m)

lo = initial length (m)

$\varepsilon = \text{strain}, \qquad \text{unit} - \text{less}$

When the stress and strain of a material is known in a material, it is possible to calculate the Young's Modulus of a material. This relationship is known has Hooke's law. Young's Modulus defines the elastic properties of the material, it can be used to determine resistance to elastic deformation. If a material is loaded over its elastic limit, it permanently deforms. A low Young's Modulus means that the material is elastic, while a high Young's Modulus tells that the material is stiff and inelastic.

Young's Modulus of a material can be expressed as:

$E = stress \, / \, strain$ [27]

$= \sigma \, / \, \varepsilon$

$= (Fn \, / \, A) \, / \, (dl \, / lo \,)$

2.2.5.1 Stress and strain behavior in polymers

Several soft polymeric materials show viscoelastic behavior when undergoing deformation. Viscoelastic materials have the tendency to experience creep and stress relaxation. [27]

Creep, which is continued deformation, happens when the material is subjected to a constant load over time. It occurs when the material is subjected to a long-time stress which is below the yield stress. This stress can be induced by compression, tension, or shear loading. [27]

Stress relaxation causes a decrease in stress when the part is held under a constant strain over a period of time. Stress relaxation is usually expressed as induced stress a function of time. [27]

It is also worth mentioning, that at very low temperatures, polymers become rather rigid and brittle. Well below glass transition temperature, the mechanical characteristics change in the polymeric material. The polymer undergoes a so called ductile to brittle transition. When this occurs, the material is more likely to fracture. The failure in this case is described as a low strain fracture at the highest stress. [28]

2.3 Mechanics of bicep-triceps movement (agonist-antagonist movement)

The human arm contains many muscles which works together to perform many different motions so we can perform all sort of tasks which are essential in our everyday life. One of them being the agonist-antagonist movement, the flexing movement of the bicep and triceps. When the bicep muscle is contracting, it creates a movement which bends the arm towards the shoulder. During this episode, the triceps (antagonist) are relaxed. Vice versa, when triceps are contracting the hand extends back to initial position, lengthening the arm. In other words, when one of the muscles is contracting, the other is relaxing allowing the movement to occur. The agonist movement is referred to as the prime mover, which initiates the movement whilst the antagonist muscle is the secondary mover. [24]

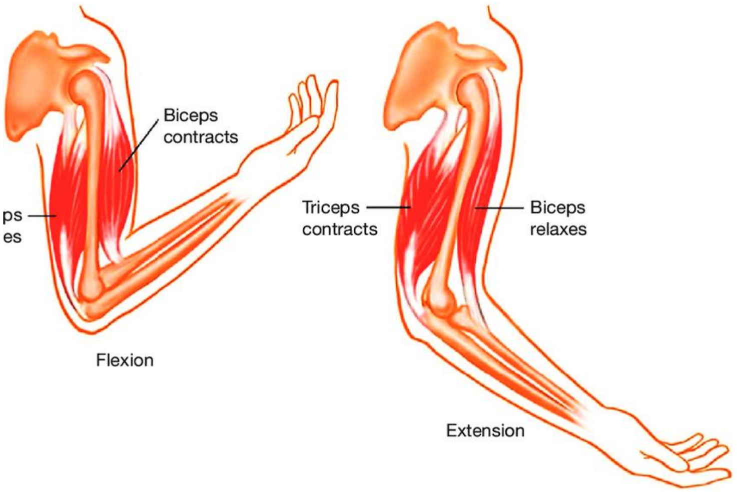


Figure 3: The flexion and extension movement of an arm [24]

Physiological cross-sectional area (PCSA) is the measure of the maximum cross-sectional area of the muscle perpendicular to its fibers. PCSA is used to measure the muscles ability to produce force. In general, the larger the PCSA, the greater the force production is. Additionally, the muscles mechanical output also depends on its moment arm and the length of the muscle. Biomechanical models have shown that the brachialis and biceps brachii muscles contributes to the elbow flexion torque the most. [25]

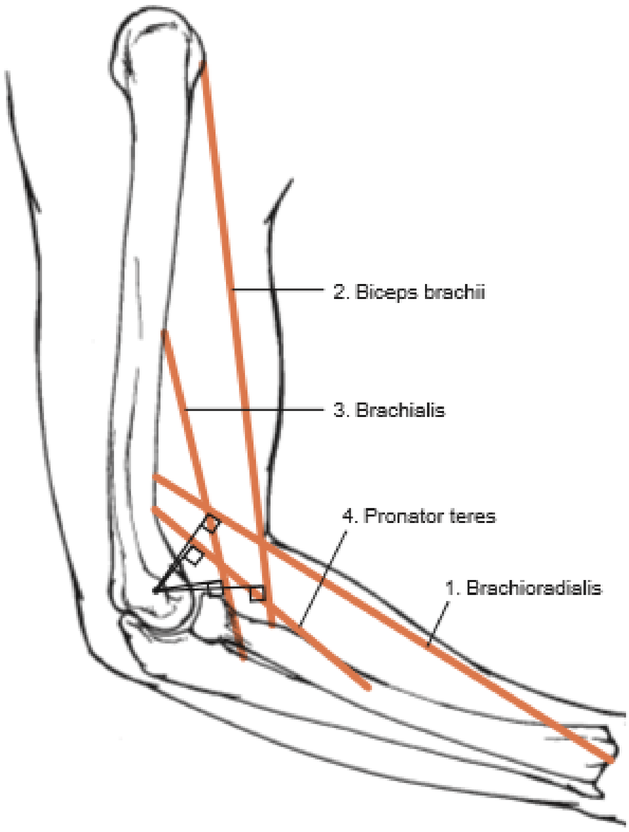


Figure 12.10: The moment arms of the primary flexor muscles of the elbow. A muscle's moment arm is measured as the perpendicular distance from the point of rotation to the muscle pull. In order of longest to shortest moment arms, the muscles are *1*, brachioradialis; *2*, biceps brachii; *3*, brachialis; and *4*, pronator teres.

Figure 4: Flexor muscles of the elbows [25]

2.3.1 Force and moment

When the muscle shortens it produces tensile force. When this happens, the muscle produces a moment. This occurrence can be described as muscle strength, and can be calculated with the following formula:

$\mathrm{M} = \mathrm{rF}$ [25]

Where,

$\mathrm{M} = \text{ is the moment generated (Newton/meters, N/m)}$

$\mathrm{F} = \text{ tensile force of muscle (Newton, N)}$

$\mathrm{r} = \text{ distance from point of rotation (meters, m)}$

The force required to support the forearm and hand (force generated by biceps brachii, in this simplified version) can be illustrated with the following two-dimensional system:

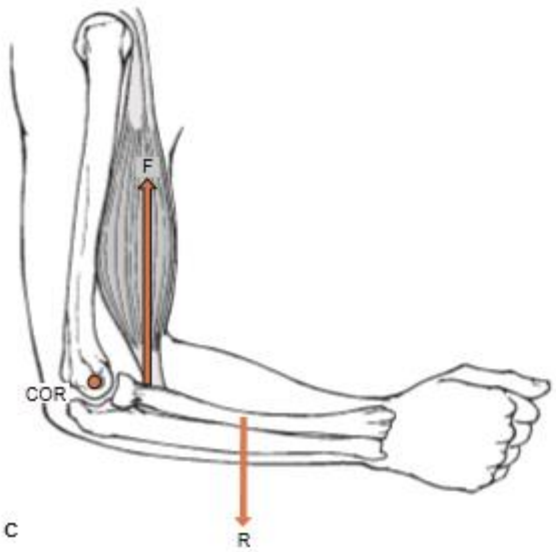


Figure 5: Simplified version of the muscle forces [25]

Here, F is the exerted force, R is the reaction force and COR is the center of rotation. This movement system represents a third-class lever. Almost all human body movements are third class levers, where the muscle force is between the COR and reaction force.

2.3.2 Mechanical work, energy, and power

Mechanical work is the product of force and distance, which is given in Joules. When work is done energy is being transferred from one place to another, for example the energy required to move an object a certain distance.

Work can be expressed as:

$\mathrm{Work} = \mathrm{Ns}$ [26]

Where,

$\mathrm{N} = \text{Force (Newton, N)}$

$\mathrm{s} = \text{distance (meters, m)}$

Power is the rate of what work is being done, how much energy is being transferred in a certain time. Power is usually given in watt.

$\mathrm{Power} = \frac{\mathrm{Work}}{\mathrm{time}}$ [26]

Energy of a system refers to it capacity to perform work and has therefore unit Joules. It can be divided into potential energy (stored energy) and kinetic energy (energy of motion.) [26]

2.4 Biomechanical problems of stroke patients

A stroke occurs when the brain is unable to receive oxygen and nutrients from a blood vessel. This commonly happens when the blood vessel is either blocked by a clot (Ischemic stroke) or it ruptures or breaks (Hemorrhagic stroke), resulting in loss of brain cells and blood vessel. This can affect the patient's ability to think, talk and move. [37]

Most of the stroke patients will have some problems with movement after a stroke that are usually caused by weakened muscles. It is common for stroke patients that only one side of the body is affected by this debilitation. Other disturbances after the stroke may include abnormal movement synergies, lack of movability and unusual postural adjustments. This negatively affects the persons arm functions, such as reaching, grabbing, and gripping, which are all vital for performing daily activities such as grooming, toileting, eating, moving, and dressing. [38]

According to clinical studies, rehabilitation for upper limb patients have proven to be prosperous in the recovery of the patient. Therefore, it is recommended that the upper limb post stroke patient starts the rehabilitation process immediately by correcting their arm movement so that it returns to normal. Main treatment for these patients includes a suitable arm rehabilitation device to regain normal arm function as soon as possible. [38]

2.5 Soft robotic devices that support arm movements

As stated before, assistive arm rehabilitation devices play a vital role in the rehabilitation process of the patient. To combat the shortcomings of the traditional rigid rehabilitation devices, soft robotic devices offers a promising alternative due to its lightweight and increased compliance to the human body. The lack of rigid components also removes constraint restriction and allows for more natural biomechanical movement.

Kari Love and Matthew Borgatti designed a soft robotic elbow orthosis, the Neucuff, for cerebral palsy therapy. When pressurized, the inflating elements become rigid which causes the arm to extend. This wearable device offers a powerful tool for rehabilitation which improves the patients arm movability problem. It implements the soft robotic technology by using soft materials to make it easy and comfortable to use it. [39]

Figure 6: Neucuff, a soft orthotic exoskeleton [39]

Soft rubbery polymeric materials, such as silicone rubber, are also used in Pneumatical Artificial Muscles (PAMs). One well-known example of a PAM is the McKibben muscle, which have been used in different orthotic devices since the 1950's. A McKibben muscle is usually constructed of a soft inflatable silicone rubber tube covered with a braided mesh and clamps at the ends. [40]

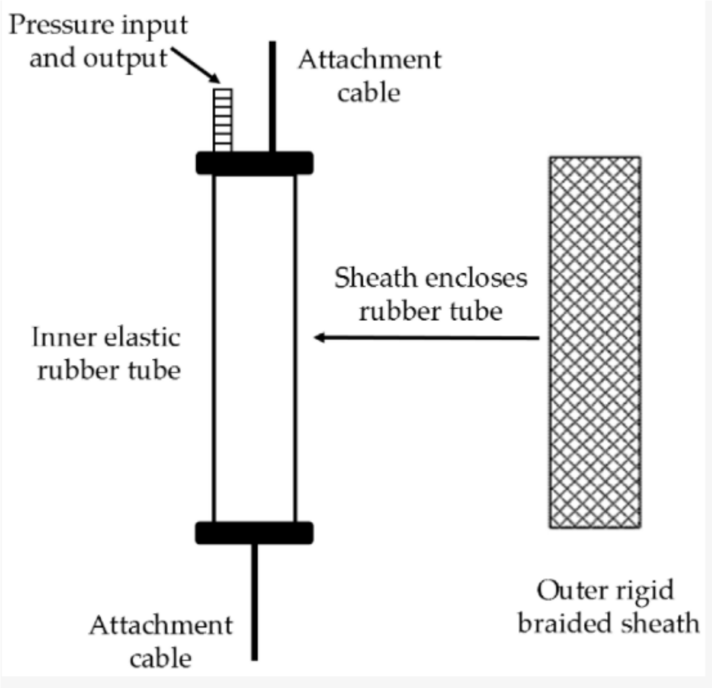


Figure 7: A setup for a pneumatic McKibben actuator [32]

The movement in the artificial muscle is produced by pressurizing the internal bladder forcing it to expand. When this happen the muscle contracts and the diameter thicken whilst the length shortens. This is usually done by compressed air via a barbed air fitting which is placed in one end of the pneumatic artificial muscle. [32]

2.6 Design, manufacturing, and testing of soft robotic devices

Because soft robotics is an interesting and emerging field of robotics, many innovative ways have been developed to design and manufacture such soft components.

Soft robotic systems have been usually designed using traditional 3D computer-aided software's such as AutoCAD or SolidWorks. Such software's offer a relatively simple way to design and simulate a product protype using various textures and colors. The 3D design file can be easily shared with others, enhancing early visibility for a product.

Such programs have some problems, however. It is hard to simulate complex non-homogeneous materials often used in modern soft robotic devices. Custom finite element methods have been used to generate soft robotics designs. Programs such as VoxCAD allows simulation of multi-materials with hard and soft structures. [29]

The manufacturing of a soft robotic device is usually done by moulding. The process usually involves mixing a polymer, such as silicone rubber, in a mould. Moulds can easily be 3D-printed using commonly available 3D-printers. [30]

Due to advancements in 3D-printing technologies, various additive manufacturing technologies have also been used in directly printing the soft robotic device. Early AM methods were limited to the production of mainly rigid thermoset polymers. Now it is possible to create parts from various materials such as ceramics, elastomers, and metals. Even multi-material printing has been made possible, which allows complex constructions with potentially electrical circuits embedded in them. [30]

3 METHOD

This chapter is divided in two main sub-sections. One of the main objectives in this chapter is to explain step by step the process of producing the silicone elastomer ethanol composite material in a 3D printed mould. Section 3.1 introduces the production of the mould, introduction of the materials used, manufacture process of the silicone ethanol and the actuation of the material using heat. The composite material was produced in Arcada University of Applied Science. The second part of this chapter 3.2. introduces the design and testing simulation done in SolidWorks 2019.

3.1 Production of the composite

3.1.1 Mould design

Two different moulds were designed using SolidWorks 2019. The moulds were designed as prototypes for testing the phase change functionality for the actuators. Both moulds were created using Extrude Boss/Base feature by first creating an outer rectangle. The smaller, inner rectangle was created by offsetting the outer rectangle by 2 mm and by using Cut Extrude feature. The outer dimensions for the smaller mould are: 14 mm (height), 19 mm (width) and 89 mm (length). Inner dimensions for small mould: 12 mm (height), 15 mm (width) and 85 mm (length). The bigger mould has the outer dimensions: 17 mm (height), 24 mm (width) and 114 mm (length). Inner rectangle dimension for bigger mould: 15 mm (height), 20 mm (width) and 110 mm (length).

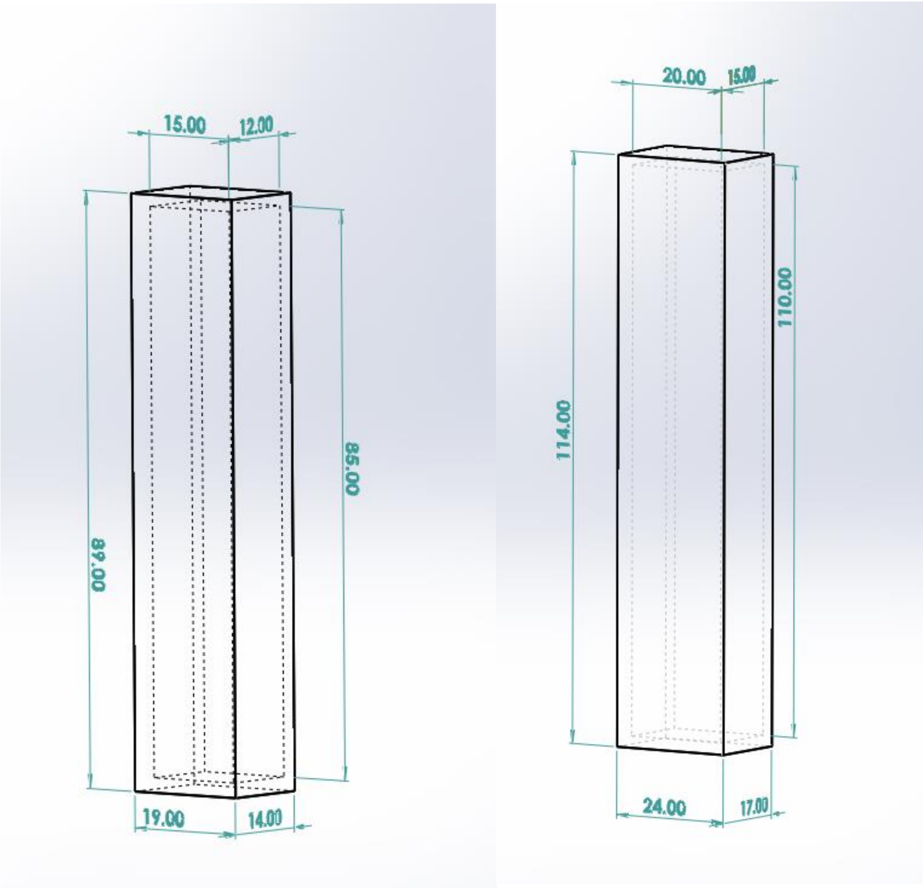


Figure 8: Mould drawings in SolidWorks (mm)

The moulds were then printed using a Creality CR 10 3D printer. PLA filament was used as material for the moulds. The author decided to 3D print the mould due to ease and accuracy of fabrication. PLA was chosen as material due to its low toxicity, and because it is affordable and derived from renewable resources.

Figure 9: 3D-printed mould

3.1.2 Materials

The composite material produced in this thesis includes a matrix material, which is a commercially available two-part mould silicone, Addition Curing RTV-2 Mould Silicone 1520. [31]

Figure 10: Addition Curing RTV-2 Mould Silicone 1520

The matrix material was chosen based on its ease of fabrication, ability to cure in room temperature, its resistance to high temperature, its good tearing resistance and due to its mechanical properties to produce high strains while withstanding high stresses. Properties of the silicone can be seen in Table 1.

Color	Elasticity (%)	Hardness Shore A	Tear strength (N/mm)	Viscosity 23 °C (mPas)	Tensile strength (N/ mm^2)	Shrinkage after 7 days
Clear	500	20	> 30	8 000	> 4	≤ 0,1

Table 1: Properties of Addition Curing RTV-2 Mould Silicone 1520. [31]

The working time is 40 minutes and setting time is 8 hours for the silicone rubber. Mixing ratio of component, A to B is 1:1. Ethanol (≥ 95%) was used as a phase change material. Ethanol was chosen because of the chemical compatibility with the matrix material, due to its low toxicity and adequate boiling temperature. It is known from previous contact angle experiments, that silicone rubber wets the ethanol good which is important for the experiment. [8]

3.1.3 The manufacture of silicone ethanol composite

After the mould was ready, the two-part silicone rubber was mixed with the ethanol. Several samples were produced using two different concentrations, one being ethanol 40 % and 60 % silicone rubber. Other samples were produced with concentrations 30 % ethanol and 70 % silicone rubber. The samples produced with 30 % ethanol and 70 % silicone rubber showed very little or no expansion when heated up to temperature of 78,2º C. Therefore, the author decided not to include them in this thesis. The material was prepared by mixing the ethanol with the silicone rubber component A for about 2 minutes in a glass beaker. After that, the silicone rubber component B was added and mixed for an additional 2-3 minutes until the ethanol was absorbed with the liquid silicone. Some of the samples were moulded with a piece of a resistance wire. A nickel-chromium wire with a DC resistance of 4 Ω/m and diameter of 0,6 mm was used for the experiment. A piece of the resistance wire was cut to about 160 mm with 3 coil setup with diameter of 10 mm. The rest of the samples were moulded without a wire. The viscous material was poured in the mould and left to cure overnight.

3.1.4 Actuation of the material

After curing, the samples were removed from the mould. Two different methods were used to actuate the material: electrical heating by connecting the resistance wire to a DC power supply (Thurlby Thandar PL310QMT) and heating using a hot plate.

3.1.4.1 Electrical heating using resistance wire

The specimen with dimension 17 mm (height), 24 mm (width) and 114 mm (length) was placed on a stand. Alligator clips were connected to the resistance wire from the DC power supply in order to heat the material. The machine output voltage was set to be 1,31 Voltages and current to 2092 milliAmperes, to get the highest possible power to heat the material. The tempartue of the specimen was constantly measured from one side of the specimen using an electronic thermometer while being actuated on the stand as can be seen in Figure 11. After 5 minutes and 26 seconds, the specimen temperature reached about 60 degrees Celsius. At this point the wire started overheating and failed. The specimen showed no visible expansion, which is expected since the material did not reach the phase transition temperature. Other experiments done with the same type of wire, showed also undesired results. The wire did not manage to heat the material so that it would have reached 78,2º C. The reason for the failure of wire was probably due to that the wire was experiencing overheating. The wire simply could not withstand the given current and voltage, and therefore failed before reaching the phase transition temperature.

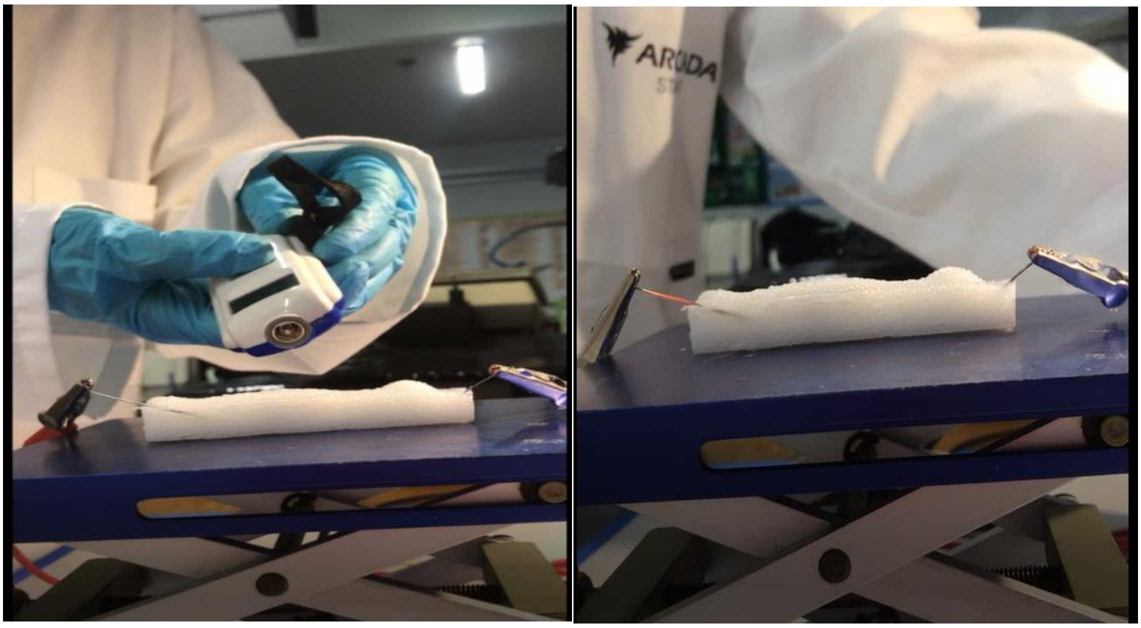


Figure 11: Left picture shows the start setup. Right picture shows the failed wire

Unfortunately, due to the government decision to close the school due to the COVID-19 pandemic, the author was unable to conduct more experiments using a different type of resistance wire to heat up the material.

3.1.4.2 Heating with hot plate

Since the wire heating failed, the author decided to try another method of actuation. A hot plate was chosen for this experiment, due to the availability and ease of use. A smaller specimen, with the starting width of approximately 68,5 mm was placed in a glass beaker and placed on the hot plate. Vertically drawn line was measured to be 14,6 mm.

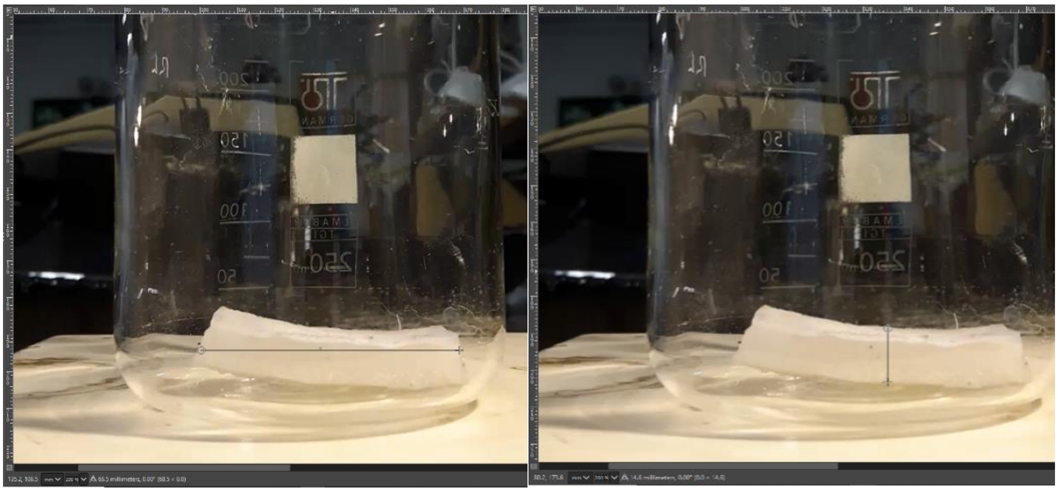


Figure 12: Starting dimensions for sample, horizontal (left): 68,5 mm and vertical (right): 14,6 mm

A camera was attached on a stand to record the expansion. The temperature change was measured using an electronic thermometer from the side of the specimen. The temperature reached 80 ºC after 52 seconds.

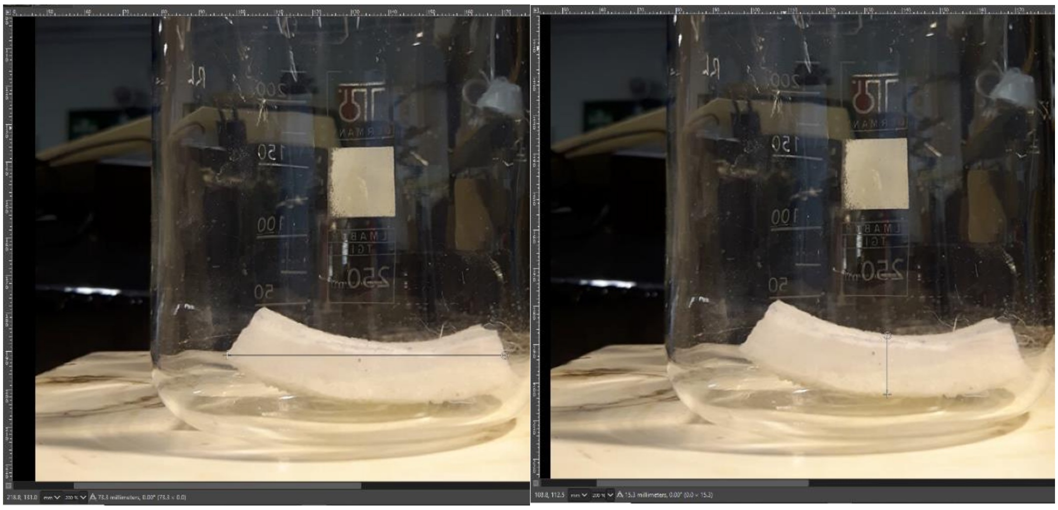


Figure 13: Final dimensions for sample, horizontal (left): 73,3 mm and vertical (right): 15,3 mm

The growth in area after 52 seconds compared to the starting dimensions was approximately 12 %. It is, however, hard to measure the exact expansion this way since the sample was not completely straight to begin with and this method does not measure tree dimensional expansion. Since the heating was done using a hot plate, the heating was uneven which caused the sample to curl upwards which resulted in anisotropic expansion.

3.2 Design of the product using SolidWorks

The product was designed using SolidWorks. The product is designed for a person that still has some mobility left in the arm, e.g. for a person that has experienced a stroke. The stress test was also done in SolidWorks, to determine that the actuator can withstand required force.

The main objective was to create a product that is simple, affordable, comfortable, and safe for rehabilitating a stroke patient. It could also of course be used by patients with other similar injuries or disabilities.

Before starting, the author did some research in available arm rehabilitation devices and studies related to the subject. A suitable design for this project was to create an actuator that would use a McKibben type of muscle. Even though most of artificial McKibben muscles are usually actuated hydraulically or pneumatically, the basic idea behind it can still be applied in this design. This artificial muscle would be connected to a stretchy and comfortable sleeve that would be worn by the patient.

The actuator should fulfill the following requirements:

- The actuator part (mimicking the bicep muscle) should be made from silicone rubber and ethanol
- Must be able to support the forearm, hand and additionally 5 kg
- Easy to use and comfortable
- Preferably economical
- Fit an arm with BMI around 21

The sleeve design is based on the authors own arm measurement.

First the arm span was measured to determine the length of the sleeve. The distance from upper bicep to where hand start was measured to be 430 mm. It was decided that 330 mm would be a good length for the sleeve.

Additionally, three different circumference measurements were taken to create a design that would fit the arm as good as possible. The following measurements were obtained: 1. Circumference 280 mm 2. Circumference 230 mm 3. Circumference 190 mm.

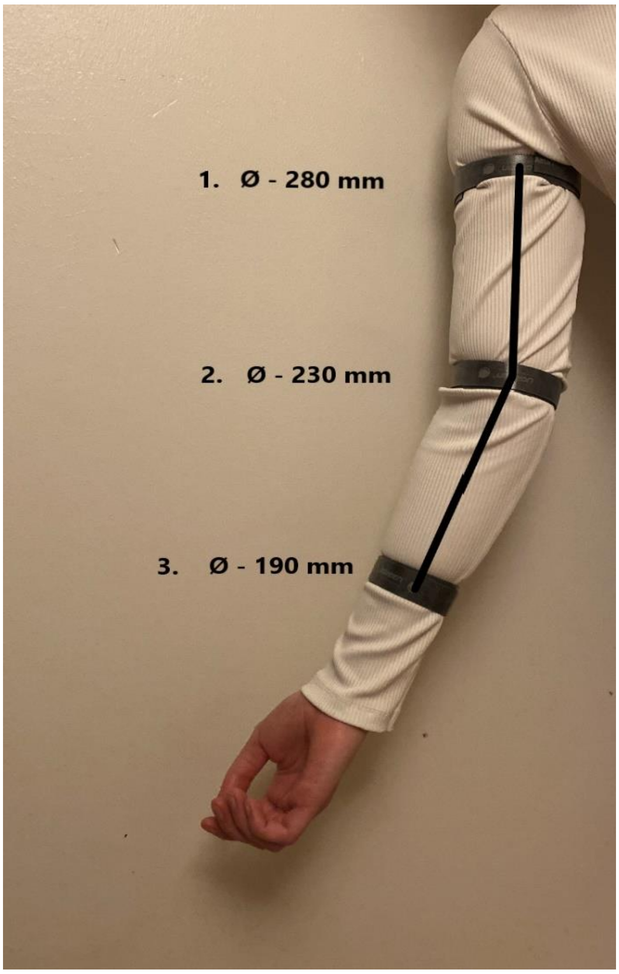


Figure 14: Measurements of the arm

3.2.1 The design procedure

After the measurements were taken, the first sketches were done in SolidWorks.

Firstly, the end parts of the sleeve were created using the smallest (190 mm) and the largest (280 mm) circumference. Both parts are designed with a fastener in the middle of the circle to attach these parts to the silicone actuator. The parts were created by first sketching a circle and offsetting it by 2 mm. After this, the parts were extruded 50 mm.

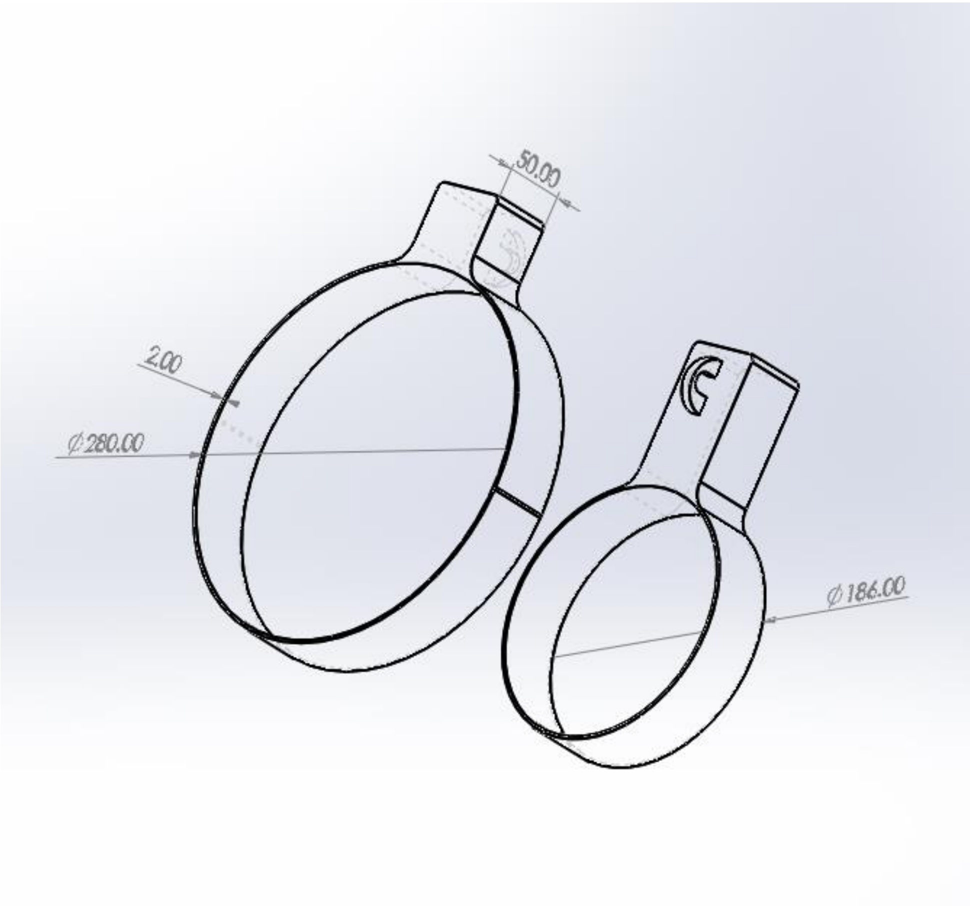


Figure 15: Largest and smallest part of the sleeve

The fasteners were drawn on the right plane on the square plate. First an outer half-circle was drawn with diameter 40 mm. An arc with diameter 15 mm was drawn inside the semi-circle and extruded with 8 mm. The purpose of these fasteners is to connect the sleeve with the silicone elastomer actuator. Both fasteners are identical to each other and located at the end parts of the sleeve.

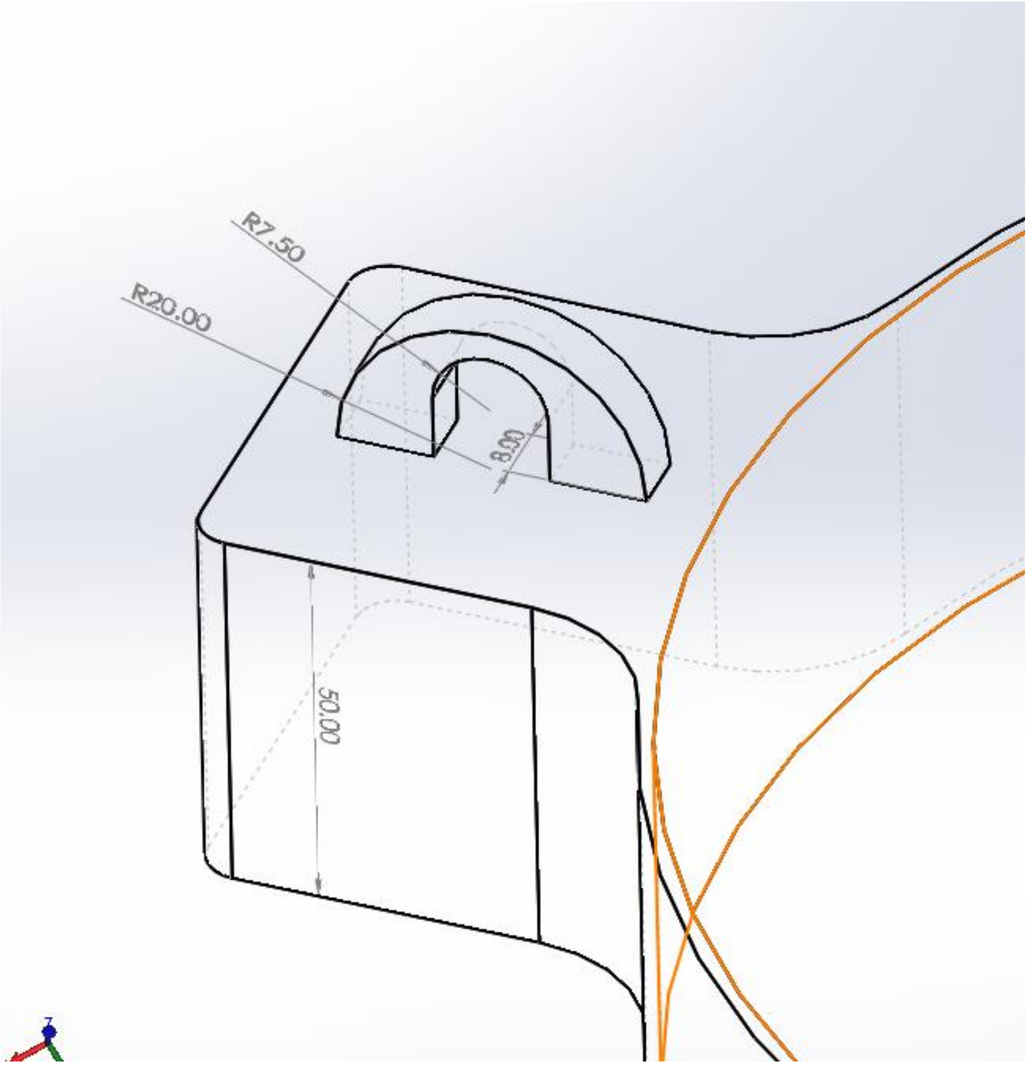


Figure 16: Fasteners

Next, the middle parts of the sleeve were created using with the of the circumference measurements from the middle part of the arm. The parts were created by first sketching a circle (280 mm and 230 mm) on the top plane, and then offsetting that plane by 130 mm and 100 mm, and sketching new circles on those planes with circumferences 230 mm and 190 mm. The circles were then joined to a part using the loft tool. Lofted cut was used to make the part hollow inside. Thickness of the sleeve was set to be 2 mm in these parts also.

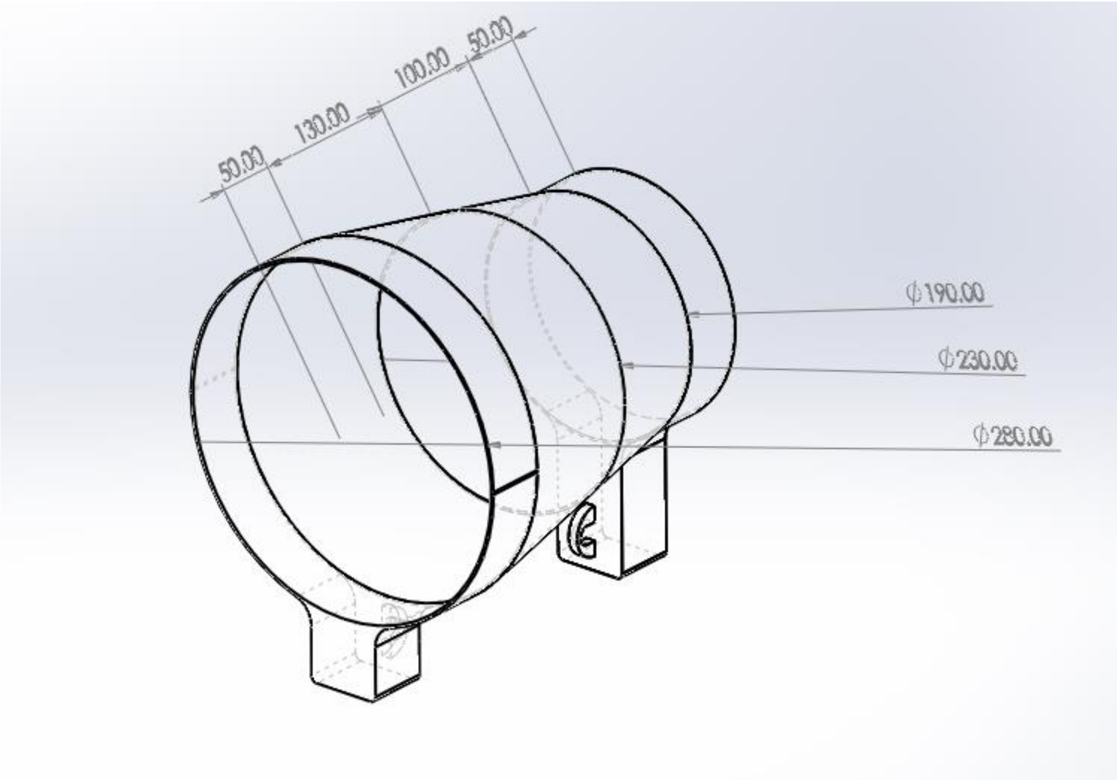


Figure 17: Middle parts assembled with rest of the sleeve

The fabric here would be made of a stretchy neoprene material, except for the square plates and fasteners that would be made of a more rigid plastic like ABS.

Much like the McKibben muscle, the actuator needs clamps at the ends so that the silicone cylinder part can contract. For this reason, two similar knobs were created to fit the end of the silicone elastomer piece. A circle with diameter 42 mm was sketched on the top plane and extruded 35 mm. An extruded cut of 20 mm was done to the bottom side of the piece, for the soft expandable part to fit in there. These knobs are connected to the fasteners in the sleeve, and therefore also have fasteners that can be connected to the square plates. The knob has a 1 mm hole in the middle for the resistance wire. These knobs would be made from a more rigid and robust material, like ABS.

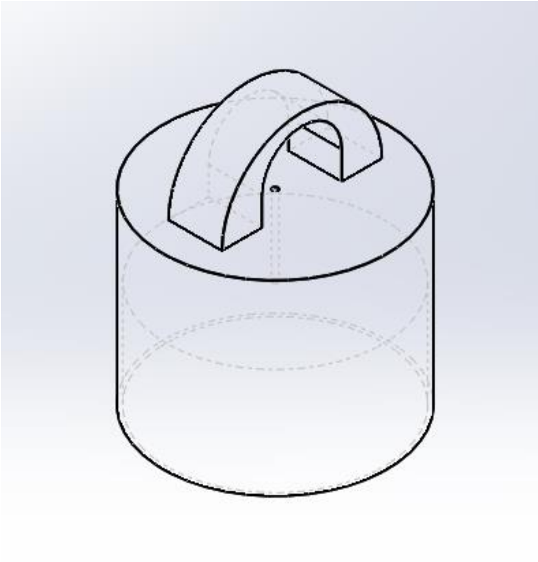


Figure 18: Isometric view of the knob

After this the cylindrical, expandable silicone composite part was created. The circumference was set to be 40 mm and the part was extruded 156 mm. A helical structure with diameter of 20 mm, 156 mm in length with 12 revolutions, was sketched and placed inside the silicone elastomer to represent the resistance wire. The helical structure has a thickness of 0,25 mm, which is the thickness of the resistance wire. Additionally, a braided mesh sleeving of thickness 0,5 mm was introduced on top of the silicone actuator as a protective cover.

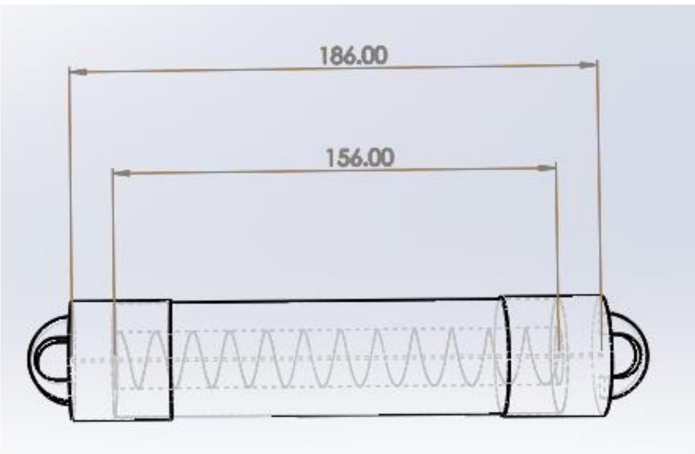


Figure 19: Assembly of the actuator

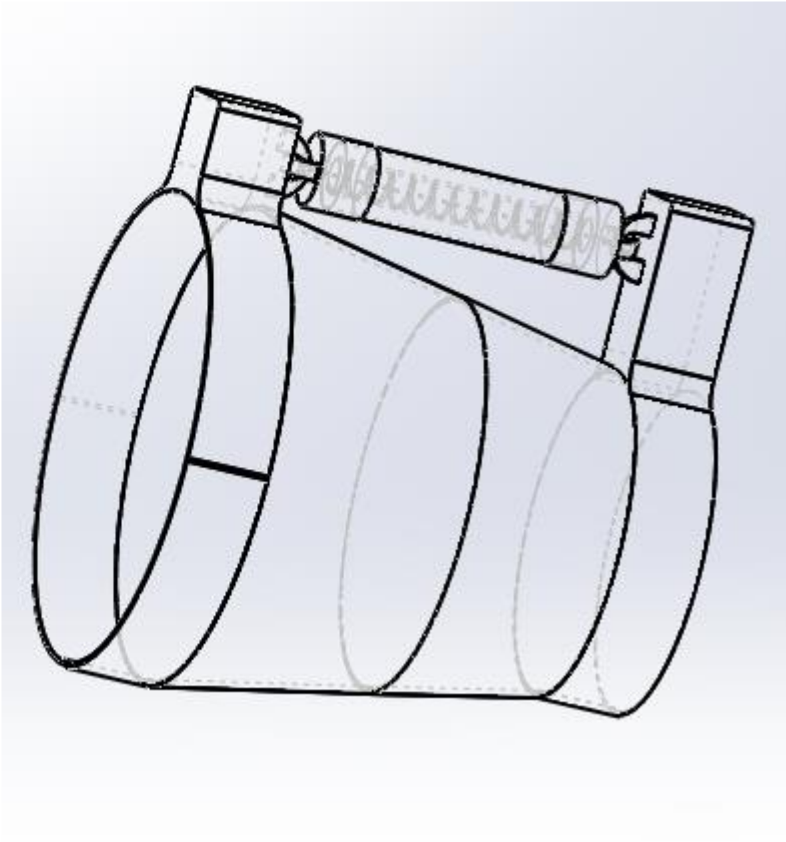


Figure 20: Actuator attached to the sleeve

Lastly, a Velcro band was created for the top and bottom part of the sleeve to make it more adjustable. The Velcro bands are attached to the top and bottom part with a buckle and a fastener. The buckle would be made of a hard plastic, such as Nylon.

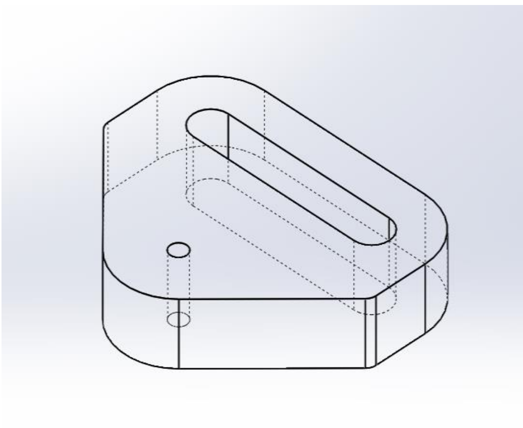


Figure 21: Buckle that the strap is attached to

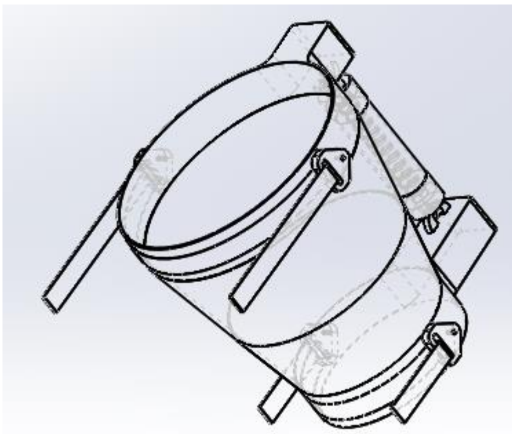


Figure 22: Straps for adjusting the sleeve

The resistance wire would be connected to a power source to actuate the silicone rubber composite material. A small power source could be attached to the sleeve design. The author has not enough knowledge to design such electronic power supply for this purpose, so that is why it was left out from this design.

Figure 23: The final product

3.2.2 Test simulation of the actuator

Because most of the force would be applied to the actuator, this part was chosen for the simulation. As stated before, one of the objectives for the product was that it would be able to support the forearm, hand and additionally 5 kg. Calculations were done to determine how much force is exerted to the actuator when it is held stationary at 90 degrees. This can be calculated using the equilibrium formula that states $\Sigma F = 0$ and $\Sigma T = 0$. [25]

To do this, all the forces need to be identified that have a moment arm and can create a torque. An estimated mass of total 1,174 kg [25] is given to the forearm and hand. Length from COR to the palm is measured to be approximately 0,3 m. Center of gravity for the forearm and hand is 0,15 m. Additionally, a mass of 5 kg is added. This mass is placed in the persons palm. Gravitational acceleration is calculated with value $9{,}81\ \mathrm{m/s^2}$. The actuator would be attached approximately $0{,}107$ m from the COR.

Force	Magnitude and direction (N)	Moment Arm (m)	Torque ($T = FMA$) (Nm)	Torque Name
W_o	$-\ 49{,}05$	0,3	$-14{,}715$	T_o
W_{h+f}	$-\ 11{,}51$	0,15	$-1{,}726$	T_{h+f}
F_a	(+) Unknown	0,107	Unknown	T_a

Table 2: Values for calculating the force in the actuator

Where,

W_o = Weight of object held in hand (49,05 Newtons)

W_{h+f} = Weigt of hand and for − arm (11,51 Newtons)

F_a = Force required to support the for − arm, hand and 5 kg

We solve for torque in the actuator,

$$\Sigma T = 0$$

$T_a + T_{h+f} + T_o = 0$

$T_a = - T_{h+f} - T_o = 0$

$T_a = -(-14{,}715 \text{ Nm}) - (-1{,}726 \text{ Nm}) = 16{,}441 \text{ Nm}$

The actuator must create a torque of $16{,}441\ Nm$ to prevent angular acceleration.

The force the actuator must create to support the for-arm, hand, and 5 kg:

$T_a = F_a \times MA_a$

$F_a = T_a \div MA_a = 16{,}441 \text{ Newtons} \div 0{,}107 \text{ m} = 153{,}65 \text{ Newtons.}$

The following values were set for the SimulationXpress. A custom plastic material was created, and average values of Polydimethylsiloxane were set for the simulation.

Properties of Polydimethylsiloxane:

Elastic Modulus: $(380 - 870 \text{ KPa})$ Avg $= 625 \text{ kPA} = 0{,}625 \text{ MPa}$ [35]

Poissons ratio $= 0{,}5$ [35]

Mass density $= 965 \text{ kg/m}^3$ [34]

Tensile or fracture strength $= 0{,}625 \text{ MPa}$ [35]

Yield strength $= 700 \text{ kPA} = 0{,}700 \text{ MPa}$ [33]

Since the values are average values for PDMS, the material values may not correspond unconditionally to the actual composite material which would be produced of a combination of PDMS material and ethanol. PDMS is a viscoelastic polymer, which means it creates nonlinear elasticity. In SolidWorks SimulationXpress, it is only possible to conduct a linear deformation study and because of this the results might not represent how the material would behave under such circumstances.

The actuator design was changed to a one part to perform the test simulation. Fixtures were added to one of knobs, and 200 Newton force was added on the bottom part of the actuator to simulate the force exerted to the actuator to support the forearm, hand and additionally 5 kg. The lowest factor of safety found in the design was 2.37247.

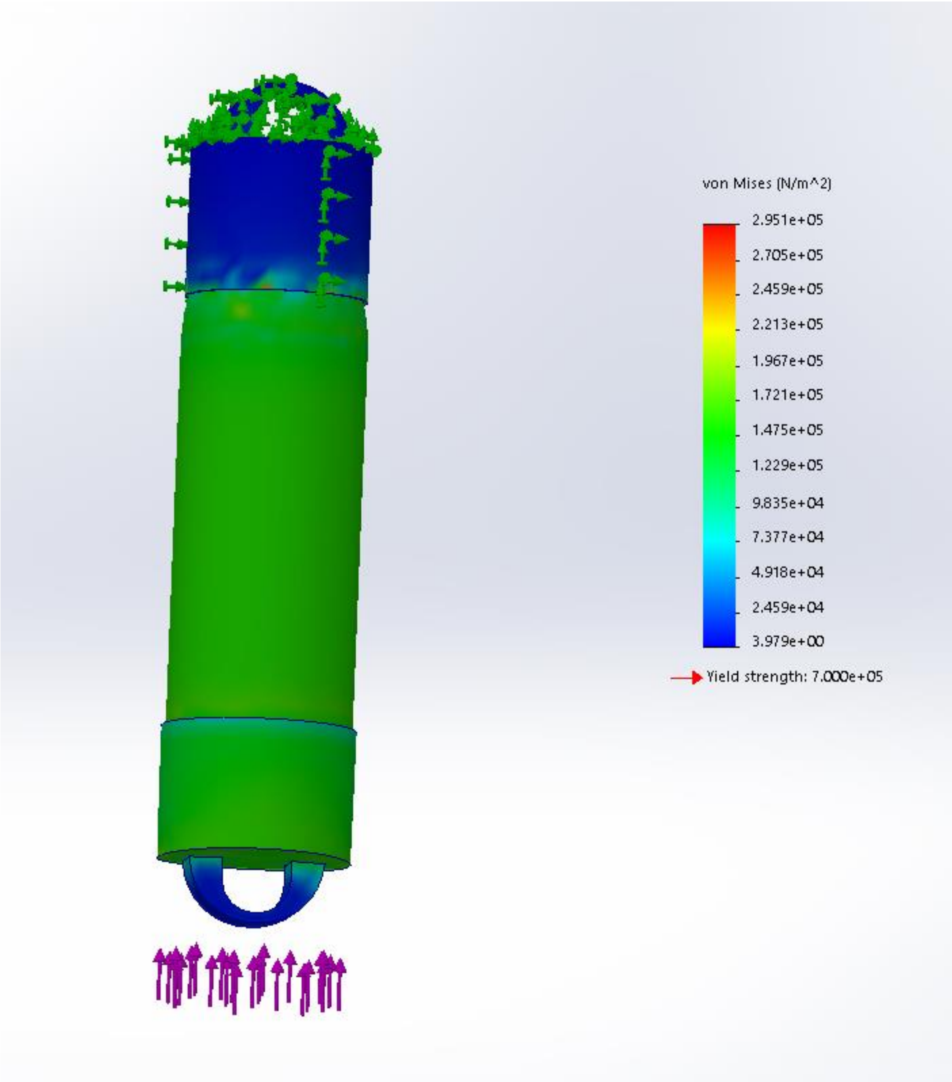


Figure 24: Test result of the simulation done in SolidWorks SimulationXpress

4 RESULTS AND DISCUSSION

4.1 Production of the composite

The fabrication process of the composite silicone elastomer ethanol material turns out to be relatively uncomplicated and inexpensive. Many times, when moulding a silicone rubber, there is a concern that there will be air bubbles trapped against the surface if not mixed correctly. It can be very time consuming and difficult to avoid the bubbles. In this thesis work however, this was not a concern since the bubbles were desirable, which made the moulding process very easy. The moulds were also easily printed with a commercially available 3D printer using PLA as printing material. A perk of using PLA as a mould material is that it is derived from renewable resources like corn starch or sugar cane, unlike many other thermoplastics that uses non-renewable resources such as petroleum in their production. Still, PLA offers a robust and cost-efficient material that can be used in variety of applications. It is a commonly used 3D printer plastic, and therefore can easily be used as a material in a 3D printed mould.

The silicone composite material showed a slight expansion when heated on a hot plate. The heating was recorder to curl the end of the specimen upwards, which was expected since the material was heated from the bottom part. This caused anisotropic expansion. The heating method would be better suited for applications where such movement is desirable, such as a robotic gripper for example. Previous studies show that the expansion should be bigger. A volumetric expansion of 915 % has been reached. [8] The results presented in this thesis were nowhere near this value.

There are many reasons why the resistance wire experiment was not successful, but it is mainly believed to be because of the faulty wire set-up. By incorporating a smarter and a more even heating system, the material is likely to produce a higher and even expansion in a shorter time.

More tests should be done to determine which set-up would have been most suitable for this purpose. The author would have wanted to try a different wire, longer piece of wire and more suitable voltage and current and to perform a tensile test to determine the mechanical properties for the specimen. Unfortunately, this was not possible due to the government decision to close the school.

A second challenge for the material was the evaporation of ethanol after heating the specimen. It was observed that the material started to lose its ability to expand and overall dryness occurred when left in open air for 10 days. This problem is a common problem in other similar experiments and should be rectified if such a material ever would be used in a rehabilitation actuator device such as presented in this thesis. One possible method to do this would be protective coating.

4.2 Analysis of the material combability to the product and improvements for future research

Regarding the production of the silicone and the material used, Addition Curing RTV-2 Mould Silicone 1520, the author would change it EcoFlex 00-50. This is mainly since many successful studies published have used said material to produce various soft robotic devices. According to a study, wetting of ethanol on EcoFlex 00-50 is better compared to other widely used soft robotic silicone rubbers. EcoFlex 00-50 is also relatively inexpensive, environmentally friendly and a certified skin safe material. [8]

The heating of the material should be done using a more suitable resistance wire. Nickel-chromium wires have been used successfully, but a longer segment of wire should be used with an adjusted power. As introduced in the design done in SolidWorks, a spiral coil configuration of 12 coils with diameter 20 mm could be moulded directly inside the actuator to make the heating more uniform which would also speed up the heating process. Other heating solutions could be also considered. An electrically conductive elastomer composite material has shown promising results. It is a low-cost silicone elastomer with an expanded intercalated graphite conductive additive and can retain itself after performing large strains up to 250 %. This would also not constrain the design so much compared to a wire configuration, since the whole actuator would be soft. [36]

As mentioned earlier, shelf-life was also somewhat problematic in the material. A lot of ethanol evaporated from the actuator after the first heating. It was observed that when the used specimen was left in open air conditions for two weeks, the specimen had dried and would not be fit for usage. This could be fixed using a stretchable plastic tube, or other protective skin or coating that would extend the lifespan of the actuator. [8]

A FEM analysis could be done to predict the behavior of the object when it is being used. However, having a physically correct simulation does not always correlate to the reality, since there are many different factors that should be taken into consideration when designing a product, especially when it is designed to be in close contact with a human.

4.3 Design and simulation

The simulations done in SolidWorks shows that the actuator was able to withstand a total load of 200 Newtons without undergoing any bigger deformations, with a lowest factor of safety 2.37247. As stated before, the knob would not be produced from a similar material to the actuator, but rather from a more rigid material such as ABS and would therefore not behave like that in real life. The actuator would also have a protective braided mesh sleeve with thickness of 0,5 mm. This could unfortunately not be tested since SolidWorks SimulationXpress does not allow multi-material testing. The testing did not take into consideration the fact that the material is a composite and would therefore contain 20-40 % ethanol. Composite materials deform generally more unpredictably due to their non-homogenous structure.

Another problem with the testing was that SolidWorks SimulationXpress only allows testing for materials that deforms linearly with an increasing load. Many plastics, such as the PDMS, deforms in a non-linear fashion. This could have been tested with e.g. SolidWorks Simulation Premium but unfortunately the author did not have access to this software or other similar software that could have conducted such studies. If one were to build such an actuator in real life, mechanical evaluation could be done with a blocked force test while actuating the specimen by heating and measuring the maximal pulling force. It can be concluded that more conclusive tests and simulations should be conducted to better determine how the material would deform before allowing it to interact with a human.

5 CONCLUSIONS

A literature review of the following subjects was performed: soft robotics in healthcare, safety, soft robotic materials, design, and current devices.

After the literature review, experiments were done to produce a silicone ethanol composite material for the soft robotic device. A small expansion was observed when the specimen was heated with on a hot plate and reached the phase change transition temperature (78,2 ºC). The experiments using the resistance wire failed due to overheating of the wire. The author would have wanted to conduct more experiments using the resistance wire and do a tensile test to the specimen to measure the maximum tensile strength. Due to the COVID-19 outbreak, the experiments could not be finished.

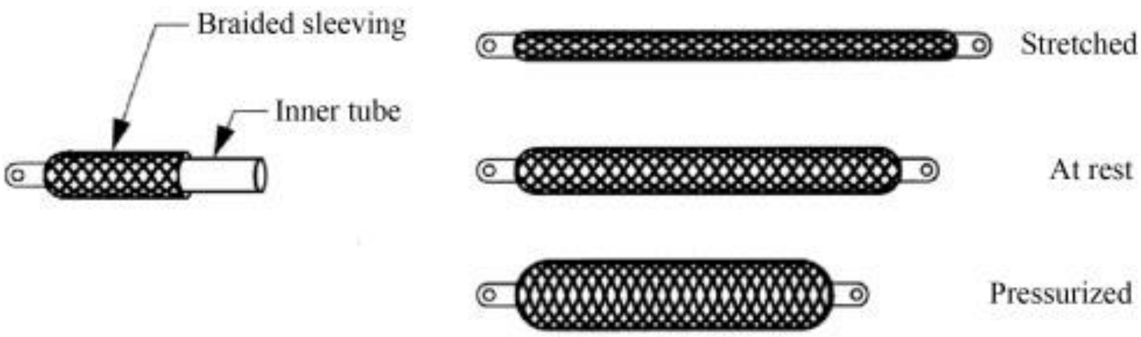
A proposition of a design that could be used for rehabilitation purposes using SolidWorks designing program was executed and tested for a force of 200 Newtons using average property values for Polydimethylsiloxane. The sleeve was done to fit a female arm with BMI around 21. However, the requirement for the actuator were only partially fulfilled since it could not be properly tested for the actual composite material it would be produced of, circumstances it would actuate and deform in since SolidWorks SimulationXpress does not provide that sort of testing. If one would produce such an actuator, it would have to be simulated and tested using other methods, SolidWorks SimulationXpress is not suitable to determine how the material would react in circumstances where a soft phase change composite material is being actuated. If one would want to simulate such a product, it is recommended that one would use a FEM simulation software for this. For mechanical force evaluation of the actuator, a tensile test should be conducted to determine the how strong the material is.

It can be concluded that the actuator produced in this thesis still require development and improvement before it would be suitable for usage as rehabilitation device. With some modifications, mainly in the heating and cooling system and in its shelf-life, the silicone elastomer ethanol composite material could have the potential to be used in an arm rehabilitation device such as presented in this thesis. It offers an interesting and an economical method of producing an actuator for rehabilitation.

6 SAMMANDRAG

Enligt WHOs rapport drabbas cirka 15 miljoner människor av stroke årligen. 5 miljoner av dem förblir permanent funktionshindrade [3]. Dessutom kommer vi år 2050 att ha ungefär 2,1 miljarder människor i åldern 60 eller äldre, visar FN:s befolkningsprognos. Dessa äldre människor har en större risk att insjukna i stroke och andra sjukdomar eller skador som förorsakar nedsatt funktion i armen. [4] Dessutom kan skador i ryggmärgen resultera i tillfälliga eller bestående sensomotoriska dysfunktioner i armar och ben. Det finns då en stor risk för patienten att insjukna sekundärt i tillstånd så som som djup ventrombos och trycksår. [6] Således är det viktigt att rehabilitera patienten så fort som möjligt för att undvika dessa sjukdomstillstånd som kan förorsaka mera skada. Olika handikapphjälpmedel behövs ofta för rehabilitering av patienten och för att förbättra återhämtningen. [7] Motoriska nedsättningar i armen påverkar negativt patientens förmåga att utföra olika armrörelser, så som att sträcka ut handen och handgrepp. Dessa rörelser är viktiga för att utföra vardagliga aktiviteter som att klä på sig, äta och dusha. [38]
Olika robotiserade hjälpmedel har visat sig vara nyttiga i rehabiliteringsprocessen, men många av dem är tyvärr dyra och svåra att använda. [7] I låg-och mellaninkomstländer har bara 5-15 % av patienterna tillgång till hjälpmedel de behöver. Således behöver vi mera ekonomiska och åtkomliga lösningar för rehabilitering.

Mjuk robotik är en lovande gren inom robotiken. Till skillnad från hårda robotar, är mjuka robotar mer flexibla och de anpassar sig bättre till olika slags omgivningar. Mjuka robotar är oftast gjorda av polymeriska material, geléer och vätskor som har en stor töjnings potential.[15] Silikonelastomerer används ofta i olika mjuk robotapplikationer för att de är lätta och relativt billiga att tillverka. Silikonelastomerer är också generellt stabila och icke-reaktiva, och kan bearbetas i en temperatur upp till 150 °C samtidigt som dess nyttiga egenskaper bibehålls. [20] I tillverkningen av mjuka robotar har man inspirerats av biologiska material och organismer. Deras elasticitetsmodul ligger nära de biologiska materialens så som muskel och skinn. De har därför möjligheten att fungera som en brygga mellan konventionella robotar och naturliga organismer. Mjuka robotar har väckt ett speciellt intresse inom den medicinska sektorn, där de har använts i olika biomedicinska applikationer som t.ex. mjuka instrument för kirurgi, ortoser och även ätbara robotar som möjliggör transport av olika läkemedel. [16] Mjuka polymeriska material, som silikongummi, har också använts i pneumatiska artificiella muskler (PAM). Ett känt exempel av en PAM är McKibben-muskeln som har använts vid olika slags ortoser sedan 1950-talet. En McKibben-muskel är oftast konstruerad av en gummislang som är insvept i ett flätat plastnät, och fästs med klämmor vid ändorna. [40]

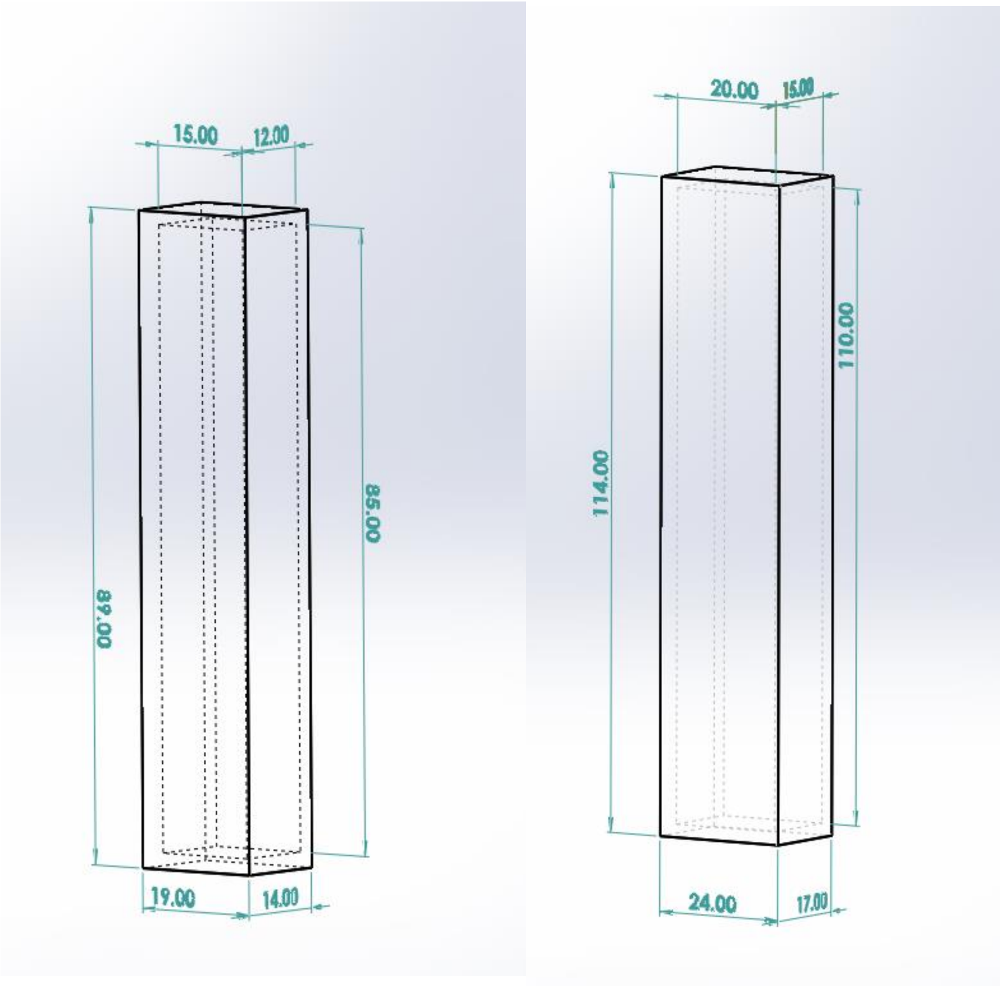


Figur 25: En McKibben muskel [40]

En McKibben muskel är oftast styrd med luft. Då den pneumatiska muskeln fylls med luft, expanderas diametern och muskeln blir kortare axiellt. Vid sammandragningen producerar muskeln dragkraft. [32]

Mjuka robotar är traditionellt konstruerade med hjälp av tredimensionella CAD program som AutoCAD och SolidWorks. De erbjuder ett relativt lätt sätt att skapa och dela med sig av sin design och prototyp, som ökar en snabb och tidig synlighet av produkten. Användaren har möjligheten anpassa sin design med hjälp av olika slags texturer och färger. Sådana program har dock vissa nackdelar, det är svårt att simulera komplexa icke-homogena materialer som oftast används i mjuka robotprodukter. Anpassade Finita Element Metoder (FEM) program har använts för att konstruera mjuka robotdesigns. Program som VoxCAD möjliggör simulering av strukturer som innehåller både hårda och mjuka komponenter. Mjuka robotar har traditionellt drivits pneumatiskt, hydrauliskt eller genom att använda elektroaktiva, termoaktiva eller polymerer med formminne där materialet drivs genom elektrisk spänning eller värme. Forskare vid Columbia University i USA, har lyckats producera ett mjukt kompositmaterial av silikongummi och etanol. Silikongummit fungerar som matrismaterial och etanolen som fasändringsmaterial. När etanol blandas och härdas med flytande silikongummi, bildas mikrobubblor över hela det komposita materialet. När materialet värms till 78,2 °C (som är fasändringstemperaturen för etanolen) eller högre, börjar etanolen koka och det lokala lufttrycket börjar stiga inuti mikrobubblorna. När trycket stiger inuti bubblorna, börjar materialet expanderas för att bli av med trycket. [8] Fasändringsändringsmaterial erbjuder en lukrativ möjlighet att driva ett mjukt robotiskt ställdon i jämförelse med traditionella elektromekaniska ställdon, då de kräver en mycket låg strömförsörjning och spänning för att drivas.

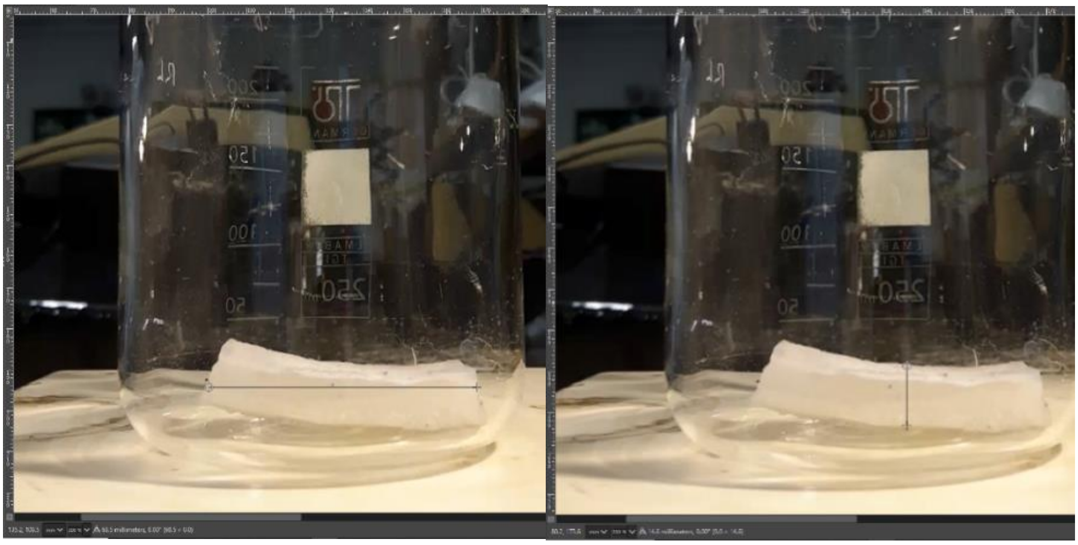
I detta arbete undersöktes möjligheten att relativt lätt och billigt tillverka ett ställdon av silikongummi och etanol som kan användas som kan användas för rehabilitering av armen. Syftet med detta examensarbete var att först producera ett kompositmaterial som gjuts i en form och efter det designa en prototyp av ett ställdon som kunde användas i rehabilitering med hjälp av 3D CAD-konstruktiongrammet SolidWorks. Efter det skulle kompositmaterialet och ställdonets kompatibilitet analyseras och på basen av detta dessutom komma på förbättringsidéer för vidare forskning. Med hjälp av SolidWorks designades först två olika former som prototyper för att testa fasförändringsfunktionen för ställdonet.



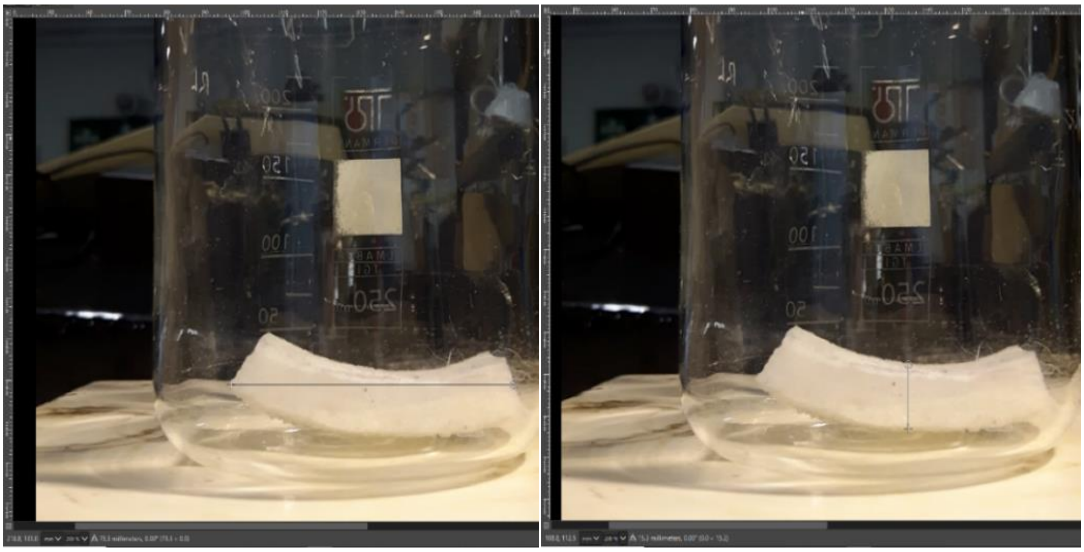
Figur 26: Formernas dimensioner (mm)

Formerna printades med hjälp av en 3D-printer, Creality CR 10, med PLA filament. Författaren valde att skriva ut formerna med en 3D-printer för att det är ett lätt och noggrant sätt att tillverka former. PLA valdes som filament på grund av dess låga toxicitet och för att den är tillverkad från förnybara resurser. Kompositmaterialet producerades av ett matrismaterial RTV-2 formsilikon 1520, och etanol $(\geq 95\%)$ som användes som fasändringsmaterial. Matrismaterialet valdes på basis av materialets förmåga att härdas i rumstemperatur, bra draghållfasthet, rivhållfasthet och töjning. Silikonet bestod av två komponenter, A och B komponent som blandades ihop med etanolen. Provbitarna producerades med två olika koncentrationer av etanol och silikon. Först producerades provbitar med 30 % etanol och 70 % silikon, och efter det med 40 % etanol och 60 % silikon. Provbitarna som producerades med 30 % etanol och 70 % silikon, visade lite eller ingen expansion, därför valde författaren att lämna bort dem från denna undersökning. Några av provbitarna härdades med en nickel-krom motståndstråd med diametern 0,6 mm och resistans 4 Ω/m. Det viskosa kompositmaterialet hälldes i formen och lämnades över natten för att härdas.

För att få provbitarna att expandera, skulle de uppnå temperaturen 78,2º C. Två olika sätt valdes för att värma upp provbitarna. Första metoden var uppvärmning med elenergi via motståndstråden. Motståndstråden var uppkopplad till en DC-strömförsörjningsmaskin (Thurlby Thandar PL310QMT). Andra metoden var att värma provbitarna på en kokplatta. Första metoden misslyckades och ingen expansion kunde nås för att motståndstråden blev överhettad före materialet han nå fasförändringstemperaturen 78,2ºC. Tyvärr kunde författaren inte utföra flera test med motståndstråden då regeringen beslöt att stänga skolorna på grund av COVID-19 pandemin. Andra metoden, som var att hetta upp materialet på en kokplatta visade bättre resultat. En mindre provbit med horisontal längd 68,5 mm och vertikal längd 14,6 mm placerades i en glasbägare och ställdes på en kokplatta.

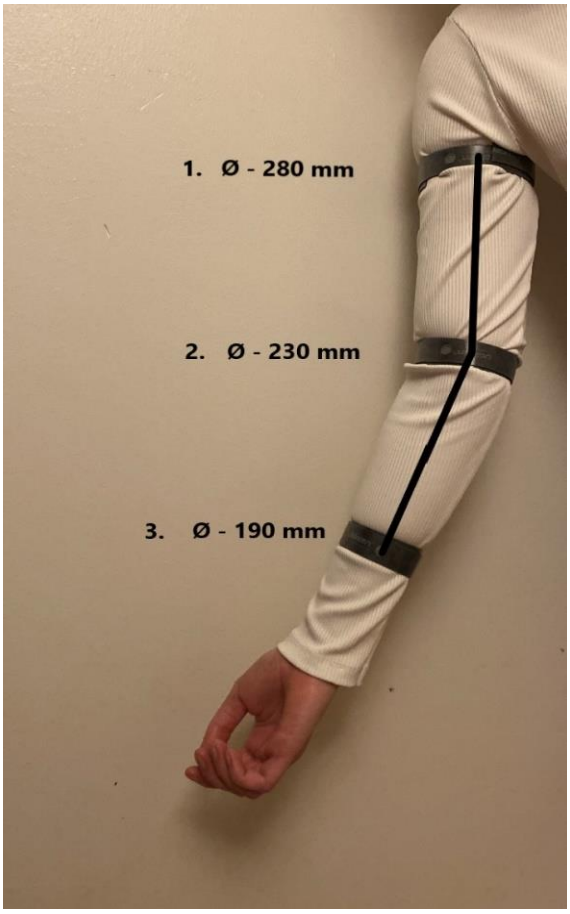

Figur 27: Provbiten före uppvärmningen

Temperaturen mättes konstant med hjälp av en digital termometer från ena sidan av provbiten. En kamera placerades på ett stativ framför provbiten för att filma expanderingen. En temperatur på 80 ºC nåddes efter 52 sekunder.


Figur 28: Provbiten efter uppvärmningen

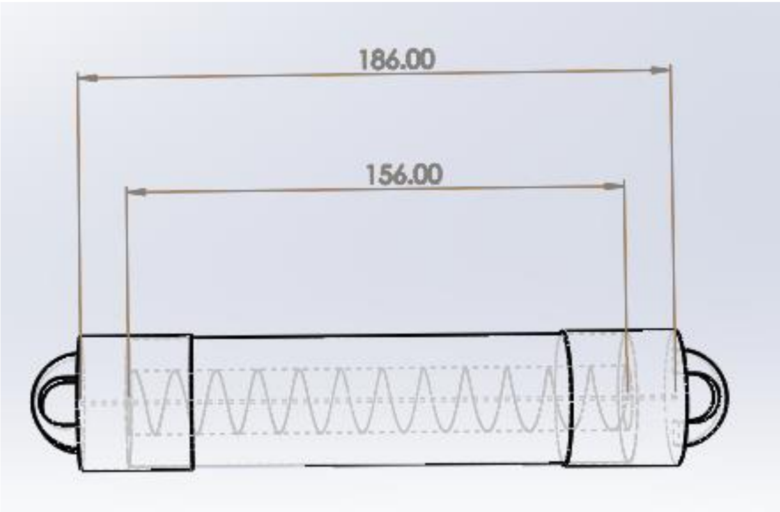
Provbitens dimensioner efter uppvärmningen: horisontala strecket: 73,33 mm och vertikala strecket 15,33 mm. Arean på provbiten växte cirka 12 % i 52 sekunder. Det är dock svårt att mäta den exakta expansionen på detta sätt, då denna metod inte tar i beaktande tredimensionell expansion. För att provbiten blev uppvärmd på en kokplatta, och all värme kom från nedre delen av provbiten, resulterade det i en anisotropisk expansion.

En prototyp av en produkt som kunde användas i rehabilitering av armen gjordes med hjälp av SolidWorks programmet. Huvudsakliga målsättningarna för produkten var att producera ett ställdon som skulle vara gjort av silikongummi och etanol, kapabel att stödja och kunna hålla upp underarmen, handen och ytterligare 5 kg i en 90 graders vinkel, lätt att använda och bekväm, lämpligtvis ekonomisk och rymmas runt en arm med BMI 21. Författaren bestämde att använda ett McKibben-liknande ställdon i designen, som skulle vara fäst i en stretchig och bekväm ärm. Produkten är baserad på författarens egna armmått, och på basis av det beslöt författaren att 330 mm är en lämplig längd för ärmen. Tre olika omkretsar mättes av armen: 1) 280 mm 2) Omkretsen 230 mm 3) Omkretsen 190 mm.



Figur 29: Armens omkretsar

Inuti det cylinderformade ställdonet skissades en spiralformad spole som skall representera motståndstråden. Motståndstråden har diametern 0,25 mm och längded 156 mm, med 12 spolar som har diametern 20 mm. Ställdonet är insvept i en 0,5 mm tjock flätad nylon mesh strumpa.



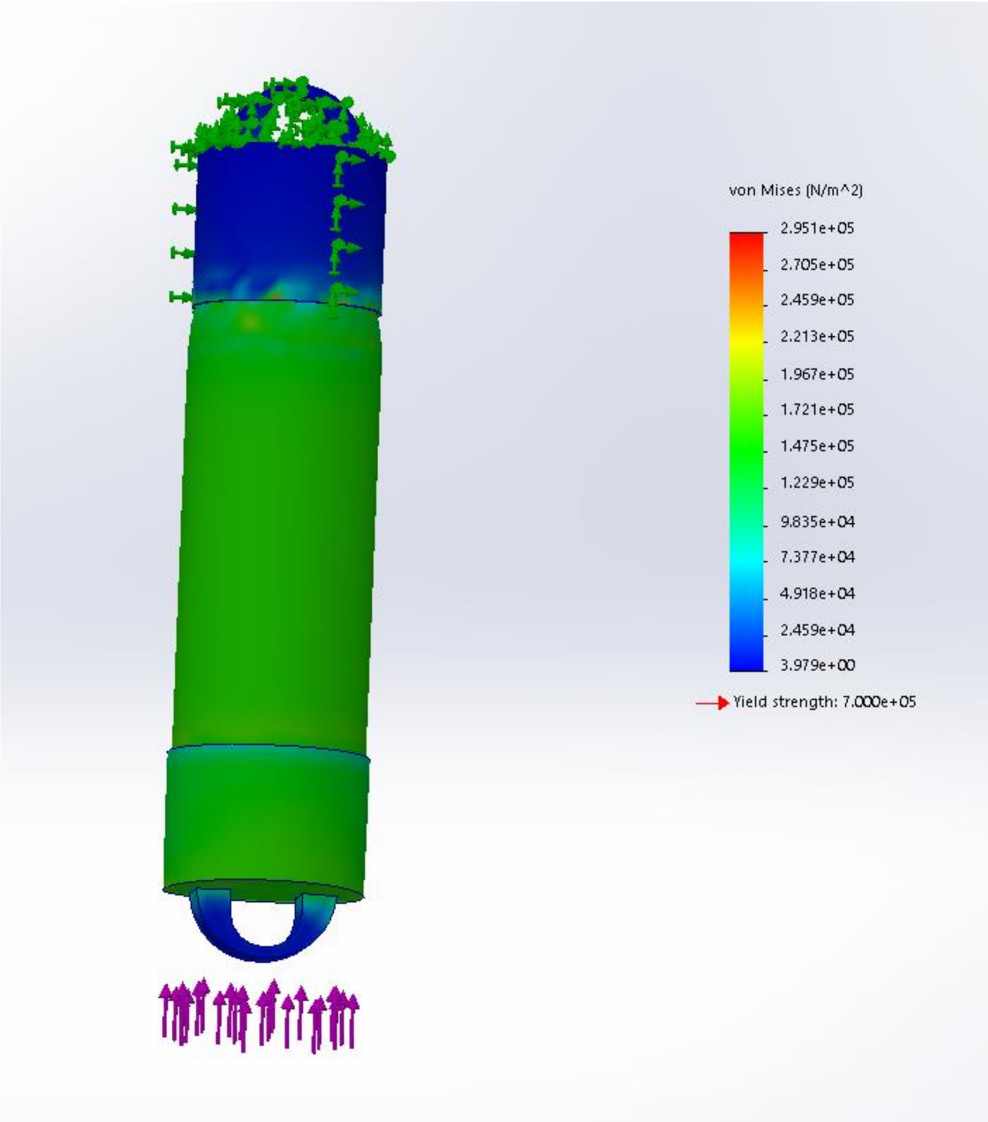
Figur 30: Ställdonet

Motståndstråden skulle vara uppkopplad i strömkälla för att driva ställdonet. En liten strömkälla kunde exempelvis vara fästad i ärmen. Tyvärr har författaren inte tillräckligt kännedom för att kunna designa en sådan strömkälla som kunde användas i ett sådant syfte, och på grund av det lämnades den bort av detta examensarbete.

Figur 31: Den slutliga produkten i SolidWorks

En testsimulering gjordes av produkten med hjälp av SolidWorks SimulationXpress. Enligt beräkningarna krävs det 153,65 Newtons kraft för ställdonet att kunna stödja och hålla upp underarmen, handen och ytterligare 5 kg i en 90 graders vinkel. Ställdonet testades för en kraft på 200 Newtons, som den klarade av med en lägsta säkerhetsfaktor på 2.37247. Dock testades ställdonet med medelvärden för Dimetylpolysiloxan (PDMS) och på grund av detta är det möjligt att resultaten inte reflekterar exakt de värden som skulle användas i ett sådant ställdon som skulle vara producerat av en kombination av PDMS och etanol. Dessutom är PDMS en viskoelastisk polymer, som betyder att den skapar icke-linjär elasticitet. I SolidWorks SimulationXpress är det endast möjligt att testa material för linjär deformation, som gör att resultaten inte nödvändigtvis representerar hur ett sådant material skulle deformeras. Detta skulle ha kunnat testas exempelvis i

SolidWorks Simulation Premium men tyvärr hade författaren inte tillgång till den programvaran eller en liknande programvara.



Figur 32: Test resultaten från SolidWorks

På grund av COVID-19 pandemin och regeringens beslut att stänga skolan, kunde inte alla experiment slutföras. Författaren skulle ha velat utföra dragprov för provbiten för att testa draghållfastheten och utföra fler test med motståndstråden. Utgående från resultaten kan man dra den slutsatsen att ställdonet ännu behöver en del utveckling och förbättring innan man kan använda det som ett ställdon för rehabilitering. Modifikationer borde göras i uppvärmnings-och kylningsmekanismen, hållbarheten och testsimuleringen. En mera lämplig motståndstråd borde användas vid uppvärmningen av materialet. En längre bit av tråd kunde tänkas användas och värmeflödet borde justeras för att nå en lämplig expansion. Genom att introducera en smartare och en mera uniform uppvärmningsmekanism är det möjligt att värma upp materialet snabbare till fasändringstemperaturen 78,2º C. Mycket av etanolen avdunstades redan efter första uppvärmningen. 14 dagar efter testet observerades det att provbiten torkat ut, och att den inte var lämplig för återanvändning. Hållbarheten kunde eventuellt förbättras genom att skydda ställdonet med plastbeläggning. Produktens draghållfasthet borde testas med dragprov. En bättre simulering kunde göras med hjälp av en FEM simulationsprogramvara. Om observerade trender inom robotiken, kan det konstateras att mjuk robotik erbjuder ett intressant och ekonomiskt sätt att producera ställdon för rehabilitering.

7 REFERENCES

[1] S. Kim, C. Laschi and B. Trimmer, "Soft robotics: a bioinspired evolution in robotics", Trends in Biotechnology, vol. 31, no. 5, pp. 287-294, 2013. Available: https://www.researchgate.net/publication/236198827_Soft_robotics_A_bioinspired_evolution_in_robotics. [Accessed: 5 April 2020].

[2] C. Majidi, "Soft-Matter Engineering for Soft Robotics", Advanced Materials Technologies, p. 1800477, 2018. Available: https://onlinelibrary.wiley.com/doi/full/10.1002/admt.201800477. [Accessed 5 April 2020].

[3] "WHO EMRO | Stroke, Cerebrovascular accident | Health topics", Emro.who.int, 2020. [Online]. Available: http://www.emro.who.int/health-topics/stroke-cerebrovascular-accident/index.html. [Accessed: 5 Apr 2020].

[4] "World Population Ageing 2017 Highlights", Un.org, 2017. [Online]. Available: https://www.un.org/en/development/desa/population/publications/pdf/ageing/WPA2017_Highlights.pdf. [Accessed: 5 Apr 2020].

[5] WORLD HEALTH ORGANIZATION., WORLD HEALTH STATISTICS 2019. [S.l.]: WORLD HEALTH ORGANIZATION, 2019.

[6] "Spinal cord injury", Who.int, 2013. [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/spinal-cord-injury. [Accessed: 5 Apr 2020].

[7] G. Rudd, L. Daly, V. Jovanovic and F. Cuckov, "A Low-Cost Soft Robotic Hand Exoskeleton for Use in Therapy of Limited Hand–Motor Function", Applied Sciences, vol. 9, no. 18, p. 3751, 2019. Available: https://www.researchgate.net/publication/335693661_A_Low-Cost_Soft_Robotic_Hand_Exoskeleton_for_Use_in_Therapy_of_Limited_Hand-Motor_Function. [Accessed 5 April 2020].

[8] A. Miriyev, K. Stack and H. Lipson, "Soft material for soft actuators", Nature Communications, vol. 8, no. 1, 2017. Available: https://www.nature.com/articles/s41467-017-00685-3#Fig4. [Accessed 5 April 2020].

[9] "Definition of ROBOT", Merriam-webster.com, 2020. [Online]. Available: https://www.merriam-webster.com/dictionary/robot?src=search-dict-hed#h1. [Accessed: 19 Apr 2020].

[10] D. Yates, C. Vaessen and M. Roupret, "From Leonardo to da Vinci: the history of robot-assisted surgery in urology", BJU International, vol. 108, no. 11, pp. 1708-1713, 2011. Available: https://www.urotoday.com/images/stories/documents/bjui/dc9bbe761c0d960c76003ef3231b45d3.pdf. [Accessed 19 April 2020].

[11] M. Moran, "Evolution of robotic arms", Journal of Robotic Surgery, vol. 1, no. 2, pp. 103-111, 2007. Available: https://link.springer.com/article/10.1007/s11701-006-0002-x. [Accessed 19 April 2020].

[12] B. Williams, "An Introduction to Robotics", Ohio.edu, 2020. [Online]. Available: https://www.ohio.edu/mechanical-faculty/williams/html/PDF/IntroRob.pdf. [Accessed: 19 Apr- 2020].

[13] H. Abidi and M. Cianchetti, "On Intrinsic Safety of Soft Robots", Frontiers in Robotics and AI, vol. 4, 2017. Available: https://www.frontiersin.org/articles/10.3389/frobt.2017.00005/full. [Accessed 19 April 2020].

[14] H. Wang, M. Totaro and L. Beccai, "Toward Perceptive Soft Robots: Progress and Challenges", Advanced Science, vol. 5, no. 9, p. 1800541, 2018. Available: https://onlinelibrary.wiley.com/doi/full/10.1002/advs.201800541. [Accessed 20 May 2020].

[15] C. Majidi, "Soft-Matter Engineering for Soft Robotics", Advanced Materials Technologies, vol. 4, no. 2, p. 1800477, 2018. Available: https://onlinelibrary.wiley.com/doi/full/10.1002/admt.201800477. [Accessed 19 April 2020].

[16] M. Cianchetti, C. Laschi, A. Menciassi and P. Dario, "Biomedical applications of soft robotics", Nature Reviews Materials, vol. 3, no. 6, pp. 143-153, 2018. Available: https://www.nature.com/articles/s41578-018-0022-y. [Accessed 20 May 2020].

[17] L. Cabeza, Advances in Thermal Energy Storage Systems. Elsevier Science, 2014, pp. 201-203.

[18] M. Boda, R. Phand and A. Kotali, "Various Applications of Phase Change Materials: Thermal Energy Storing Materials", International Journal of Emerging Research in Management and Technology, vol. 6, no. 4, pp. 167-171, 2017. Available: https://www.researchgate.net/publication/316618882_Various_Applications_of_Phase_Change_Materials_Thermal_Energy_Storing_Materials. [Accessed 19 April 2020].

[19] E. Joyee and Y. Pan, "Multi-material Additive Manufacturing of Functional Soft Robot", Procedia Manufacturing, vol. 34, pp. 566-573, 2019. Available: https://www.sciencedirect.com/science/article/pii/S2351978919309515. [Accessed 19 April 2020].

[20] S. Shit and P. Shah, "A Review on Silicone Rubber", National Academy Science Letters, vol. 36, no. 4, pp. 355-365, 2013. Available: https://www.researchgate.net/publication/257808467_A_Review_on_Silicone_Rubber. [Accessed 19 April 2020].

[21] "Ethanol", Pubchem.ncbi.nlm.nih.gov, 2020. [Online]. Available: https://pubchem.ncbi.nlm.nih.gov/compound/Ethanol. [Accessed: 19 Apr 2020].

[22] T. Huhtamäki, X. Tian, J. Korhonen and R. Ras, "Surface-wetting characterization using contact-angle measurements", Nature Protocols, vol. 13, no. 7, pp. 1521-1538, 2018. Available: https://users.aalto.fi/~rras/publications/111.pdf. [Accessed 19 April 2020].

[23] J. Simpson, S. Hunter and T. Aytug, "Superhydrophobic materials and coatings: a review", Reports on Progress in Physics, vol. 78, no. 8, p. 086501, 2015. Available: https://www.researchgate.net/publication/280115341_Superhydrophobic_materials_and_coatings_A_review. [Accessed 19 April 2020].

[24] N. Nayak, "Skeletal muscle", Elsevier Ltd., vol. 4, pp. 795-801, 2016. Available: https://www.researchgate.net/publication/301621001_Skeletal_muscle. [Accessed 19 April 2020].

[25] C. Oatis, Kinesiology. Philadelphia, Pa.: Lippincott Williams & Wilkins, 2009, pp. 228-244.

[26] C. Oatis, Kinesiology. Philadelphia, Pa.: Lippincott Williams & Wilkins, 2009, pp. 19.

[27] C. Oatis, Kinesiology. Philadelphia, Pa.: Lippincott Williams & Wilkins, 2009, pp. 21-34.

[28] "Plastic Library", Polymerdatabase.com, 2020. [Online]. Available: https://polymerdatabase.com/polymer%20classes/Intro.html. [Accessed: 19 Apr 2020].

[29] D. Rus and M. Tolley, "Design, fabrication and control of soft robots", Nature, vol. 521, no. 7553, pp. 467-475, 2015. Available: https://dspace.mit.edu/bitstream/handle/1721.1/100772/SoftRoboticsReview-FinalAuthorVersion.pdf;jsessionid=41E3FF239F554009FF09DF4A928F18C0?sequence=1. [Accessed 20 April 2020].

[30] F. Schmitt, O. Piccin, L. Barbé and B. Bayle, "Soft Robots Manufacturing: A Review", Frontiers in Robotics and AI, vol. 5, 2018. Available: https://www.frontiersin.org/articles/10.3389/frobt.2018.00084/full. [Accessed 20 April 2020].

[31] MUOTTISILIKONI 1520 1 kg trans 1:1 | Kevytrakentajan verkkokauppa", Kevytrakentajan verkkokauppa, 2020. [Online]. Available: https://www.kevytrakentajanverkkokauppa.fi/tuote/muottisilikoni-1520-1-kg-trans-11/. [Accessed: 04 May 2020].

[32] T. Tsai and M. Chiang, "Design and Control of a 1-DOF Robotic Lower-Limb System Driven by Novel Single Pneumatic Artificial Muscle", Applied Sciences, vol. 10, no. 1, p. 43, 2019. Available: https://www.mdpi.com/2076-3417/10/1/43/htm. [Accessed 4 May 2020].

[33] A. Santiago-Alvarado et al., "Physical-chemical properties of PDMS samples used in tunable lenses", International Journal of Engineering Science and Innovative Tech-

nology (IJESIT), vol. 3, no. 2, 2014. Available: https://www.researchgate.net/publication/261861311_Physical-chemical_properties_of_PDMS_samples_used_in_tunable_lenses. [Accessed 4 May 2020].

[34] B. Chang et al., "Capillary Transport of Miniature Soft Ribbons", Research.aalto.fi, 2020. [Online]. Available: https://research.aalto.fi/files/38398107/micromachines_10_00684.pdf. [Accessed: 04 May 2020].

[35]"PDMS", Mit.edu,2020. [Online]. Available: http://www.mit.edu/~6.777/matprops/pdms.htm. [Accessed: 04 May 2020].

[36] R. Bilodeau, "All-Soft Material System for Strong Soft Actuators", School of Engineering and Applied Sciences, Yale University, New Haven, CT, USA, 2020.

[37] T. Truelsen et al, "The global burden of cerebrovascular disease", Who.int, 2020. [Online]. Available: https://www.who.int/healthinfo/statistics/bod_cerebrovasculardiseasestroke.pdf. [Accessed: 21 May 2020].

[38] M. RAMLEE and K. GAN, "FUNCTION AND BIOMECHANICS OF UPPER LIMB IN POST-STROKE PATIENTS — A SYSTEMATIC REVIEW", Journal of Mechanics in Medicine and Biology, vol. 17, no. 06, p. 1750099, 2017. Available: https://www.researchgate.net/publication/319279926_FUNCTION_AND_BIOMECHANICS_OF_UPPER_LIMB_IN_POST-STROKE_PATIENTS_-_A_SYSTEMATIC_REVIEW. [Accessed 20 May 2020].

[39] M. Borgatti, "Neucuff Soft Robotic Exoskeleton • HAR.MS", HAR.MS, 2020. [Online]. Available: https://har.ms/portfolio/neucuff-soft-robotic-exoskeleton. [Accessed: 21 May 2020].

[40] F. Daerden and D. Lefeber, "Pneumatic Artificial Muscles: actuators for robotics and automation", Lucy.vub.ac.be. [Online]. Available: http://lucy.vub.ac.be/publications/Daerden_Lefeber_EJMEE.pdf. [Accessed: 21- May- 2020].

7.1 Figures

Figure 1: [16] D. Rus and M. Tolley, "Design, fabrication and control of soft robots", Nature, vol. 521, no. 7553, pp. 467-475, 2015. Available: https://www.researchgate.net/publication/277410991_Design_fabrication_and_control_of_soft_robots. [Accessed 19 April 2020].

Figure 2: [23] J. Simpson, S. Hunter and T. Aytug, "Superhydrophobic materials and coatings: a review", Reports on Progress in Physics, vol. 78, no. 8, p. 086501, 2015. Available: https://www.researchgate.net/publication/280115341_Superhydrophobic_materials_and_coatings_A_review. [Accessed 19 April 2020].

Figure 3: [24] N. Nayak, "Skeletal muscle", Elsevier Ltd., vol. 4, pp. 795-801, 2016. Available: https://www.researchgate.net/publication/301621001_Skeletal_muscle. [Accessed 19 April 2020].

Figure 4: [25] C. Oatis, Kinesiology. Philadelphia, Pa.: Lippincott Williams & Wilkins, 2009, pp. 228-230.

Figure 5: [25] C. Oatis, Kinesiology. Philadelphia, Pa.: Lippincott Williams & Wilkins, 2009, pp. 228-244.

Figure 6: [39] M. Borgatti, "Neucuff Soft Robotic Exoskeleton • HAR.MS", HAR.MS, 2020. [Online]. Available: https://har.ms/portfolio/neucuff-soft-robotic-exoskeleton. [Accessed: 21 May 2020].

Figure 7: [32] T. Tsai and M. Chiang, "Design and Control of a 1-DOF Robotic Lower-Limb System Driven by Novel Single Pneumatic Artificial Muscle", Applied Sciences, vol. 10, no. 1, p. 43, 2019. Available: https://www.mdpi.com/2076-3417/10/1/43/htm. [Accessed 4 May 2020].

Figure 25: [40] F. Daerden and D. Lefeber, "Pneumatic Artificial Muscles: actuators for robotics and automation", Lucy.vub.ac.be. [Online]. Available:

http://lucy.vub.ac.be/publications/Daerden_Lefeber_EJMEE.pdf. [Accessed: 21 May 2020].

7.2 Tables

Table 1: [31] MUOTTISILIKONI 1520 1 kg trans 1:1 | Kevytrakentajan verkkokauppa", Kevytrakentajan verkkokauppa, 2020. [Online]. Available: https://www.kevytrakentajanverkkokauppa.fi/tuote/muottisilikoni-1520-1-kg-trans-11/. [Accessed: 04- May- 2020].