Ethanol phase transition driven silicone actuator for soft robotic prosthetic arm.

Edwin Mwasi

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Author:	Edwin Nyakundi Mwasi
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Abstract:
In this thesis a soft actuator was built for usage in a prosthetic arm. The actuator was made from a combination of silicone and ethanol because the phase change of ethanol inside the silicone can achieve motion in the material.

The aim of this thesis was to create a soft actuator targeted for usage in the medical field. The main goal was to make the actuator and the arm lightweight, strong, portable and cheap.

The actuator mould was 3D printed from PLA plastic, the actuator was made, and different experiments were carried out on the actuator motion, and the prosthetic arm was designed using Solidworks software.

The hypothesis was that with proper design of the arm, mixture ratio of silicone (mould silicone 1520) and ethanol (actuator) the actuator will be strong enough to mimic human hand muscle movements.

The actuator achieved clearly visible movement in one of the experiments and results were recorded. Stress analysis was not done due to the COVID-19 pandemic which caused the school and laboratories to be closed for safety.

Keywords:	Origami, soft robotics, actuators, silicon mould
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Abbreviations

1. E = Young's modulus
2. m = Mass
3. N = Newton
4. Nm = Newton meters
5. g = grams
6. PLA = Polylactic acid)
7. $\mu =$ Coefficient of friction
8. G = Newton's constant
9. NiCr = Nickel-chrome

FOREWORD

I would like to thank Mr. Stewart Makkonen-Craig for his excellent supervision and guidance throughout this thesis.

I would also like to thank my partner Charlotta Mustonen for her support whenever needed and for sharing ideas in different areas.

Thank you to the examiner for taking his time to go through my thesis and finally, I would like to thank Arcada University of Applied Sciences as a whole for the best study system they have provided to the students.

1 INTRODUCTION

1.1 Background

Soft robotics can imitate the animals' complex movements. Soft robotics systems are characterized by their compliance, which allows localized deformation to be persistent and often responsive localized deformation. These features make soft robots particularly interesting for integration of biomedical devices with human tissues, and good performance in harsh or uncertain environments such as exploration in confined spaces or locomotion in uneven terrains. Soft robots can also be used in surgical procedures such as assistive devices, protheses or artificial organs for drug delivery. (Materials et al., 2019)

Advances in soft materials and engineering for additive manufacturing have made it possible to develop soft robotics with sophisticated capabilities such as jumping, complex 3D motions, gripping and releasing. This thesis will specifically focus on building actuators that will be beneficial in the medical field and researching the effectiveness of the technology in the long run.

1.2 Aims of thesis

The aim of this thesis was to investigate the 3D printing or mould-based structures that themselves could function as soft actuators. The moulded sample was to be positioned and directed with the help of origami structures or skeletons. These soft actuators will be used in rehabilitation of old people or any person in need of extra muscles or support for example in prosthetics. The main aim is to design a muscle (actuator) that will replace motors used in robots for the safety of the user (user friendly).

The students from Arcada University of Applied Sciences decided to pursue this idea because many people are in need of soft robotics especially in the medical sector. The ability to move a finger is taken for granted by many, but this is challenging task for those who are physically challenged. Finding a solution to help those in need will make a big impact in this world. Soft robotics has opened a path for this problem.

Designing robots that will adopt easily to humans' body and improve the lifestyle of human beings too.

1.3 Compliance with degree program theme

In functional materials course the student learned more about materials, their properties and applications. Students also learned how we can mimic nature in different ways and being able coexist without destroying the others. Soft robotics tend to bring robotics closer to natural life forms and makes the coexisting with humans safer to cooperate with human beings.
Soft actuator is made to mimics human muscle. Later the muscle (actuator) is passed through different experiments and tests in order to see its efficiency.

The students get to learn how phase change in liquids (Ethanol) can be very important in many applications.

2 LITERATURE REVIEW

2.1 What is soft robotics

In this world, we are surrounded with structures made of soft materials that makes it safe to coexist among each other. These structures include plants, insect silks, bacteria, brains and muscles. The human body consists of about 80 % of soft substances. This means that soft material in a human being's body is very important for the body to perform most of the function needed. For example, hands need the muscles to deform in order for it to lift something up, heart needs deformation for it to pump blood to all parts of the body, the mouth needs the lips to deform in order for the jaw to open it, eyes need deformation of the eye lens for optical focus and many other more. (Pfeifer et al., 2014)

Most of today's robots are made of hard materials such as metals and plastics which make them suitable for some situations but when it comes to adaptability, energy efficiency and safe interaction with humans, they under-perform or in some cases even create risks. This is because they lack many properties owned by their natural counterparts like softness, flexibility to safely coexist among fragile things.

In the current years, there has been huge growth in the more active use of soft soft-robotic systems. Having softness and flexibility similar to biological structures can provide a robot with more adaptively navigation through small delicate openings, hence avoiding damages in places like the human body. Furthermore, it can store and release energy which might also save a lot of energy in locomotion tasks. This makes soft robots safe, cheaper and more adaptable than the normal or traditional robots.

2.2 History

The history of soft robotics goes way back to the 1970s, where the design was based on robot grippers made out of granular materials. Later during the 1980s to 1990s, the technique advanced to elastomers, fluids and gels. The pioneers of the soft robots were James Wilson and Mahajan (Wilson, 1984, James Wilson and Mahajan, 1989). The robot in Figure 2.1 consists of an arm consisting of 4 to 5 bellows and two additional bellows used as grippers. The arm was able to move, pick up irregular shapes by bending the bellows.

Figure 2. 1 *(Wilson, 2020)*

Later in 1991 the second piece of soft robotics was published but it used tri-cellular units. The three cells were distributed along a central axis and each spanning 120°. They used this technique to make hand manipulation and walking.

The first piece of robot to work in electrorheological (ER) fluid robot grippers was published by Kenaley and Cutkosky in 1989. The first piece of soft robotics using gel in grippers (Hu et al., 1995). Later many pieces followed, and the technique is still growing.

Team Jones 1981

The arm in Figure 2.2 below is an experimental system of pneumatic muscles**.**
The robot works in a way that, air is forced into the muscle bags that expand while shrinking in length. Strings link the muscle to the bones resulting in the movement of the limbs. This robot was developed by the Original Android Company [RH-2012-Now defunct] in conjunction with the Royal College of Art. The robot hand was made to be used in a shop window display.

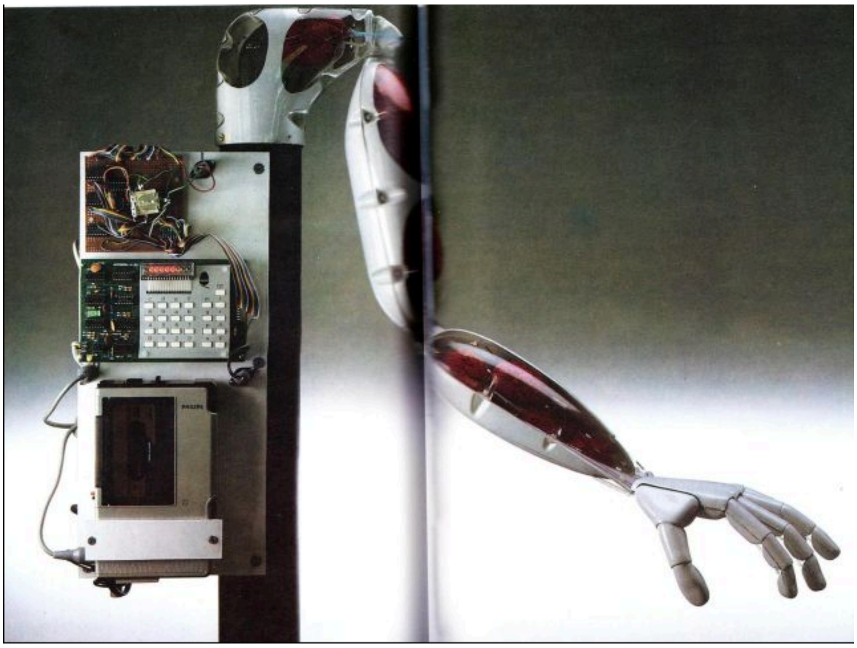


Figure 2. 2 (1981 - Pneumatic Mannequin Arm - Tim Jones (British) - cyberneticzoo.com, 2020)

Lately the research of soft robotics has improved and become more functional. People have come to realize that we really need this technology (Soft robotics) and that it is cheaper, safer, and more adaptive to different kinds of terrains. A huge amount of soft material has been synthesized and made more available to everyone. People have begun to identify the range of capabilities and limitations of soft robotics, thanks to the impressive work done by the conventional engineers in the last decades; this in turn has motivated engineers to start researching more on techniques of making soft robots.

Another important aspect is that engineers have started to integrate important components for a soft robot, for example actuators, sensors and electronics. In Table 2.1 below are some of the articles that illustrate the growth of research fields and they mostly cover the technical aspects of soft material robotic systems.

Table 2. 1 Articles of research

Reference	**History**	**Design of the material**	**Fabrication**	**Actuation**	**Sensing**	**Modelling**	**Control**	**Comments**
(Trivedi, Rahn, Kier and Walker, 2008)	×	✓	×	✓ ✓	×	✓	✓	Bioinspiration, EAPs, PAMs
(Rus and Tolley, 2015)	✓	✓ ✓	✓	✓ ✓	✓	✓	✓	-
(Bauer et al.,2014)		✓ ✓	✓	✓ ✓	✓ ✓	×	×	Energy harvester
(Wang and Lida, 2015)	✓	✓ ✓ ✓		✓ ✓ ✓	×	×	×	Categorization based on deformation and functions
Hughes et al, 2015)	✓	✓	✓ ✓	✓ ✓	✓ ✓ ✓	✓	×	Focus on manipulation and gripping

Laschi et al.,2016)	✓ ✓	✓ ✓	✓	✓ ✓	✓	✓	✓	
Kim et al.,2013)	×	✓ ✓	×	✓ ✓	×	✓	×	Bio inspiration, three case studies
Laschi and Cianchetti 2014)	×	✓	✓	✓ ✓	×	✓	✓	Categorization based on functions

2.3 Ethics

Robot ethics has been an issue talked about now and then. These issues refer to ethical problems that come up with robots, such as robots posing threat to humans' life. Some ethics are directed to healthcare whether the robots are posing some threats to sick people or not. To some extent some of the robots might be posing threats to humankind in certain ways, but this doesn't mean getting rid of all robots but instead finding a good way of making it less dangerous to the people and the environment at large.

In HRI (Health Research Institute) soft robotics promises more adaptive, swift movement within the environment and safety (Arnold and Scheutz, 2017). People have replaced their amputated hand with a prosthetic; people born with no legs can walk again using prosthetics. Soft robotics has gone to an extent of building heart valves that can help in heart diseases (Engineers design bionic "heart" for testing prosthetic valves, other cardiac devices, 2020). This all has big and positive impact in the world as a whole.

On the other hand, people may get offended by soft robotics thinking that it's going against God's will (religion) by replacing someone's heart with a soft robotic heart. The religious argument is a valid one to some extent, but one may ask, “who gave us the brains to do all these?”

There is a theoretical possibility that soft robotics can be misused to some extent, but it has shown a lot of positive sides that can be utilised to impact society in a meaningful way. In critical life and death situations, where soft robotics could be a life saver, patients who are against soft robotics might change their opinion on the technology. The other issue is that soft robotics has taken over many work opportunities from people. It is true that it has taken over some work opportunities from some people, but it has also created more work for others too. Additionally, it has also made work easier in some cases, for example soft robots lifting heavy things.
This cycle of who and what to blame may continue but the main question remains: how ready are we to work alongside with soft robotics to make a better future?

In September 2020, experts joined hands from different fields of technology, industry, the arts, law and social science at the EPSRC (Engineering and Physical Sciences Research Council) and the AHRC (Arts and Humanities Research Council) Robotics to talk about robotics, its implementation to the world and its benefits to people. (Principles of robotics - EPSRC website, 2020)

Robots are used widely all over the world, however the reality of the robots are somehow less known to the society where science fiction and media image of robots have taken over. One of the aims of the meeting was to make sure that robots technology is introduced from the beginning in order to make the public more informed about the in order for the public to open up more about the robots and their benefits. Some of the rules were impossible to address such as Asimov's famous three laws of robotics. (Asimov’s laws stated that a robot was not allowed to do anything that would harm a human being; that a robot should always obey a human; and that a robot should defend itself so long as this did not interfere with the first two rules.) (Principles of robotics - EPSRC website, 2020)

These rules were too strict in a way that they treated robots like human beings. For example, how can robots know all the different ways a human might get hurt? How can a robot know and obey all orders given by humans, whereas even humans get confused when given some instructions?

Robots should be taken as tools that help the human being's life easier. The meeting produced a set of "rules" aiming to push more discussion on the robotic issues. They stated some of the general principles concerns brought forward by the Group which could enlighten designers and users of robots in different situations. The rules were informative documentation of future discussions and not to be used as Laws.

2.4 Specific heat calculation

Specific heat calculation was one of the most important part in this experiment. The energy required to heat the material was to be enough (above 78.2°C, ethanol boiling point) in order for the actuator to work. The student researched for the formula to calculate the energy required to heat the material. The material was to be heated in respect to time. The faster the heating the faster the efficiency of the actuator. The formula was as follows:

$$Q = m \cdot C \cdot \Delta T,$$

$$Q = \eta \cdot P \cdot t,$$

$$P = V \cdot I,$$

$$t = \frac{Q}{\eta \cdot P}$$

Where:

- Q = Energy required to heat the material
- m = mass
- C = Specific heat
- ΔT = Temperature difference
- η = efficiency of the heater
- P = Heater power

- V = Voltage
- I =Current
- t = heat time

Theoretically, the calculation was based on the heating power and not taking into consideration the heater design. Therefore, the better distribution of heat throughout the material led to reduction of the heating time at the same heating power.

3 MATERIALS AND METHODS

In this chapter, the materials used are specified according to their properties. The two materials were chosen because of their easy availability and in accordance to their properties which make them suitable for this thesis project. Ethanol has a molecular formula of CH_3CH_2OH or C_2H_6O and an evaporation temperature of 78.2° C makes it suitable for this project because it evaporates faster inside the silicone and makes the silicone to expand when heated. Figure 3.1 below shows the molecular structure of ethanol. Silicone was also chosen because of the suitable property of being inert, high heat endurance and nontoxic to the environment. Silicone also provided a clear visibility of the bubbles, making it easier to measure size of the bubbles.

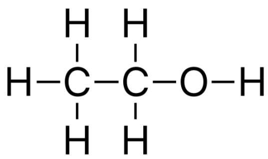


Figure 3. 1(File:Ethanol-structure.svg - Wikimedia Commons, 2020)

Table 3. 1 Ethanol properties

Property Name	Property Value	Reference
Molecular Weight	46.07 g/mol	Computed by PubChem 2.1 (PubChem release 2019.06.18)
Exact Mass	46.041865 g/mol	Computed by PubChem 2.1 (PubChem release 2019.06.18)
Color/Form	Clear	(Drugbank.ca, 2020)
Odor	Pleasant	(Drugbank.ca, 2020)
Boiling Point	78.2 °C	(Drugbank.ca, 2020)
Flash point	14.0 °C	(Pubchem.ncbi.nlm.nih.gov, 2020)

Solubility (Default)	1000000mg/L (at 25 °C)	(Drugbank.ca, 2020)

3.1 Silicone (mould silicone 1520)

Figure 3. 2 (Moulding silicones | Kevra Oy, 2020)

Mould silicone 1520 from Kevra company was used because it was one of the widely used silicone and easy to get. Silicone 1520 was also chosen because of the properties it has as shown in table 3.2 below and as explained previously above (High temperature endurance, non-toxic to environment and inert). Mould silicone 1520 is an additive cross-linkable RTV2 silicone (room-temperature-vulcanizing silicone) with high shear strength that cure at room temperature. It has a good heat resistance and its softness which makes it flexible.

Silicone 1520 does not chemically react to ethanol, hence making it good for the project. Silicone has a molecular structure of $-[Si(R_2)-O]-$ where $R = -CH_3$ is called poly (dimethyl siloxane) which is often abbreviated as PDMS. Figure 3.3 below shows the silicone molecular structure and table 3.2 shows the silicone properties.

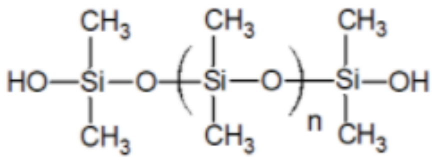


Figure 3. 3(Properties of Silicones, 2020)

Table 3. 2 Mould silicone 1520 properties

Hardness (ShoreA)	20
Viscosity 23°C (mPa.s)	8000
Shear strength (N/ mm)	>30
Tensile strength (N/mm^2)	>4
Elasticity (%)	500
Colour	Clear
Shrinkage after 7 days	≤0,1
Temperature endurance	(200°C long-term, 350°C short-term)

Features

The properties of silicone 1520 were very important to this experiment in different ways. The first property of high heat tolerance made silicone suitable for this experiment because the experiment involved high temperature heating of above 78.2 °C (Ethanol boiling point). The softness of the silicone in its solid form also helped in the manufacturing of the actuator because the actuator needs to be flexible in order to achieve different movements. The slight shrinkage of the silicone also helped in maintaining the actuator's shape for a longer period of time.

3.2 Mixability of Ethanol and silicone

Contact angle

By measuring the contact angle of the ethanol on a solid silicone, it is possible to tell how the ethanol wets silicone. In this experiment, ethanol was required to be less wetting on the solid silicone in order to make the bubbles when the silicone gel solidifies in making the actuator. This experiment was planned but it was not able to be done due to the COVID-19 pandemic.

Figure 4. 1 *(Contact Angle Measurement, Theory & Relation to Surface Energy, 2020)*

The Less contact angle, the more wetting the liquid is to the surface and vice versa.

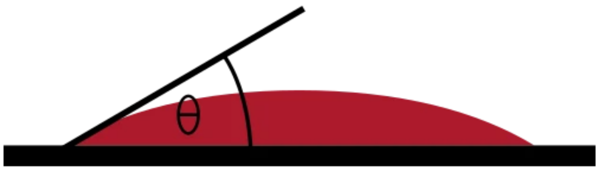
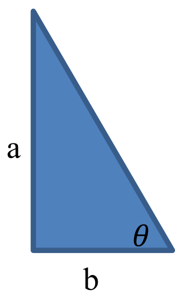


Figure 4. 2 *(Contact Angle Measurement, Theory & Relation to Surface Energy, 2020)*



Formula to calculate the angle:

$\tan(\theta) = a/b$

$\theta = tan^{-1}(a/b)$

Where:

θ = Angle

a = Opposite length

b = Adjacent length

3.3 Testometric

The stress analysis was to be performed on the pure silicone and the mixture to see how much the ethanol was going to affect the mechanical property of the actuator. This was going determine the amount of ethanol to use in real product.

Figure 4. 3 *(50kN – Testometric Co. Ltd., 2020)*

The testometric machine could have shown the flexural modulus of the mixtures and hence easy to determine the perfect balance in a more graphical way as shown below.

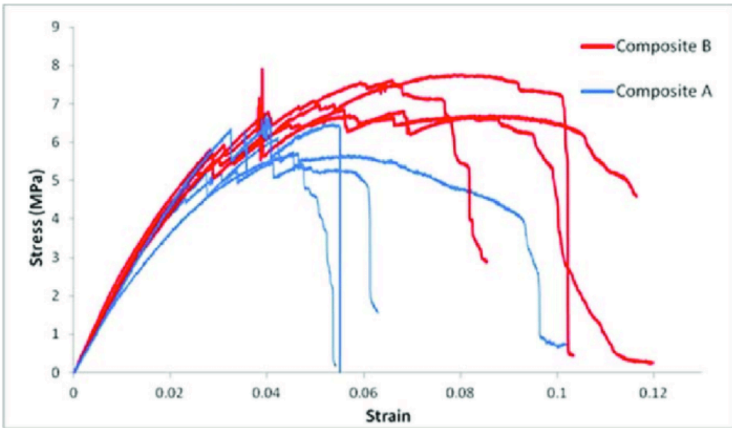


Figure 4. 4 (50kN – Testometric Co. Ltd., 2020) Graph

Let us consider composites A and B in figure 4.19 above being different designs of the specimen or with different compositions (as in this thesis, where the amount of ethanol varies). Theoretically the ethanol might reduce the tensile strength of the whole specimen due to the bubbles in it, but on the other hand more ethanol bubbles where needed for more expansion. A better balance of all the mixture would have been obtained by testing the specimen one by one and making as many samples as possible before making the final product. Again, such an analysis was not realized due to the COVID-19 pandemic.

4 EXPERIMENTS

4.1 Moulds

It was decided that two small rectangular shaped moulds were to be made based on the calculations that will be shown later. This was a good way to start before making the actual product, in order to see how the actuator will behave in small and prevent waste of materials.

The student designed the two rectangular mould samples using Solidworks software with the following measurements at the inner part before 3D printing them.

Big mould

Inner measurements 2 cm x 1.5 cm x 11 cm with the wall thickness of 0.2 cm.

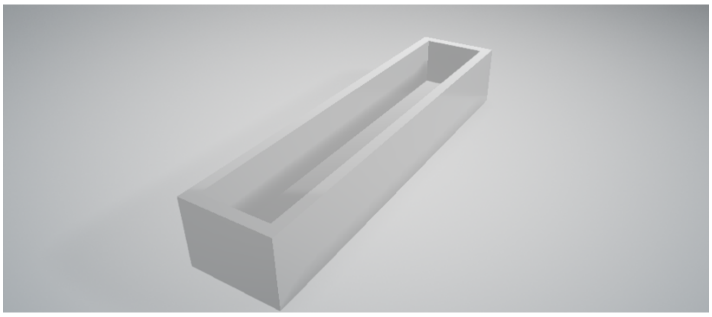


Figure 4. 5 Solidworks actuator design

Small mould

Inner measurements 1.2 cm x 1.5 cm x 8.5 cm with the wall thickness of 0.2 cm.

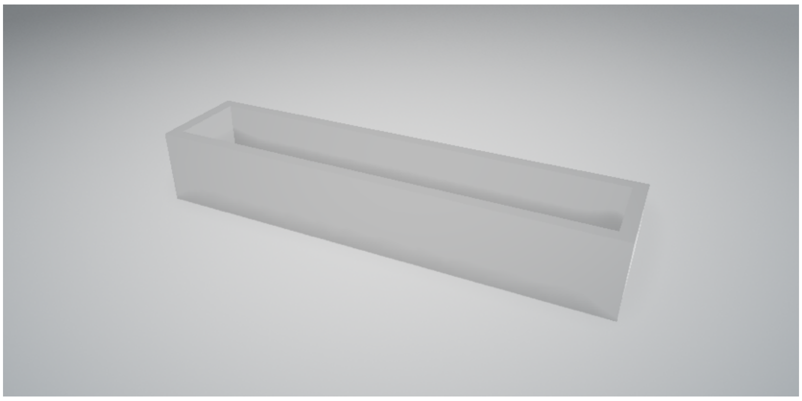


Figure 4. 6 Solidworks actuator design

The file was saved as STL file and 3D printed using PLA (Polylactic acid) with the makerbot Creality CR 10s printer which was readily available for the student in Arcada University of Applied Sciences. PLA was chosen because the actuators did not require any heating in making the moulds. PLA has a melting point of about 130 – 180 °C and hence not good for higher temperature situations.

The other reason why PLA was chosen is that it is not reactive with silicon or alcohol to the extent of affecting the actuators mixtures (Silicon and ethanol).
The 3D printer in Figure 4.7 was used to print the moulds after the design were transferred from Solidworks as an STL file to ultimaker Cura software for the 3D printer.

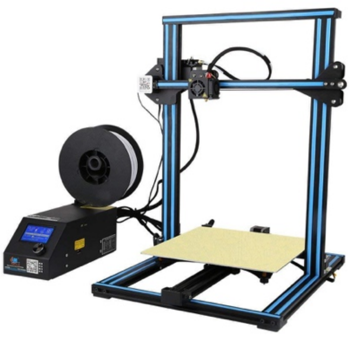


Figure 4. 7 Makerbot Creality CR 10s (Creality CR-10 / Ender, 2020)

Base layer

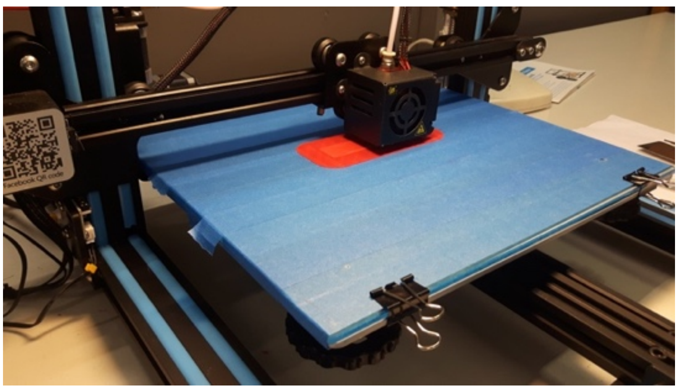


Figure 4. 8 The base layer of actuator mould 3D printing

The building plate adhesion type was set as Raft in order to provide more adhesion of the mould to the printer plate. The raft was not removed later, the students left it intentionally to provide more stability on the mould when pouring the mixture of silicon and ethanol in it.

Main mould

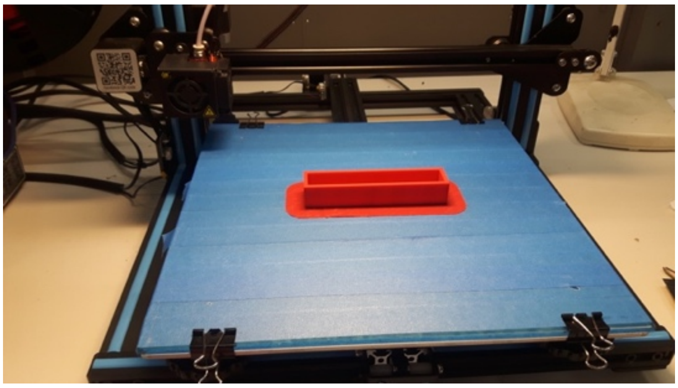


Figure 4. 9 3D printed main Actuator mould

Two moulds were created using a 3D printer with inner measurements of 2 cm x 1.5 cm x 11 cm with the wall thickness of 0.2 cm and the other one with the inner measurements 1.2 cm x 1.5 cm x 8.5 cm with the wall thinness of 0.2 cm. These moulds were only meant for experiment purposes and not for the actual product. The student decided to choose a rectangular shape mould because it was easy to measure and record the results of expansions easily. Rectangular shape was also easy to do any calculation required for the specimen, for example volume and area of the specimen that helped in the ratio mixing of the ethanol and silicone.

4.2 Actuator

The volume of the mould was calculated first before mixing the silicone with the ethanol. The silicone 1520 was mixed in the ratio 1:1 A: B. This ratio was required in order to come up with the correct soft silicone as instructed by the silicone company. Based on the previous study where 20 % ethanol was used the student decided to mix the ethanol to 40 % in the mixture of it with the silicone trying to make if more ethanol will make changes in the actuator movement.

The 40 % of ethanol was decided on the basis of making more bubbles on the silicone, hence more expansion. The specimen was to be heated by a nickel chrome (NiCr) resistance wire coiled inside it and with a PL series (Precision Laboratory) DC power supple source. Nickel chrome has a high melting point of 1400 °C making it more suitable for the experiment heating purpose. The temperature was measured using an infrared thermometer in order to get the exact temperature through of the whole specimen.

Figure 4. 10 Main actuator setup in the mould

The following mixture ratio were as follows:

Big mould

Total volume = 2 cm x 1.5 cm x 11 cm= 33 cm^3

Volume of ethanol = 33 cm^3 x 0.4 = 13.2 cm^3 = 13.2 ml

Volume of silicone =$33\ \mathrm{cm}^3 \times 0.6 = 19.8\ \mathrm{cm}^3$ (ratio 1:1 A and b) =$9.9\ \mathrm{cm}^3$ =9.9 ml each.

Small mould

$\text{Total Volume} = 1.2\ \mathrm{cm} \times 1.5\ \mathrm{cm} \times 8.5\ \mathrm{cm} = 15.3\ \mathrm{cm}^3$

$\text{Volume of Ethanol} = 15.3\ \mathrm{cm}^3 \times 0.4 = 6.12\ \mathrm{cm}^3 = 6.12\ \mathrm{ml}$

$\text{Volume of Silicone} = 15.3\ \mathrm{cm}^3 \times 0.6 = 9.18\ \mathrm{cm}^3$ (ratio 1:1 A and b) =$4.59\ \mathrm{cm}^3$ = 4.59 ml each

A 2 mm layer thickness of mixture of silicone and ethanol was put in the mould then followed by a strip of paper to give the direction on which the actuator is going to bend to. Inserting a piece of paper (Repro paper) that has a high resistance to stretch was going to limit the expansion of the silicone when heated. Below are the steps followed while making the actuator.

Step 1

Figure 4. 11 Mould step1 layer

A 2 mm thick of silicone paste was spread inside the mould in order to provide the base of the actuator. This was done carefully in order to get an equal thickness spread of the silicone.

Step 2

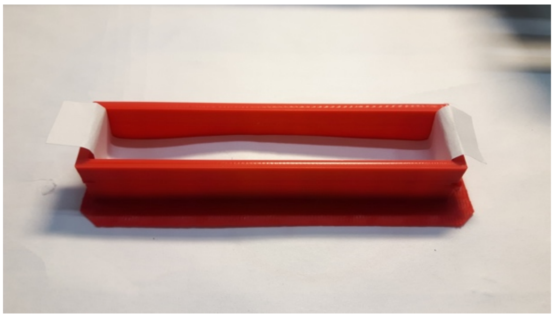


Figure 4. 12 Mould step 2 layer

A piece of paper was placed on top of the actuator mixture (Silicone and ethanol) to act as skeleton that will provide the direction of expansion of the actuator. The paper was going to hinder the actuator from expanding on the bottom side, therefore making the actuator to bend towards the paper when expanding.

Step 3

Figure 4. 13 Mould step 3 layer

The final step was to top up the remaining space with actuator mixture (silicone and ethanol) to make the full actuator expanding side. The final product was as shown below.

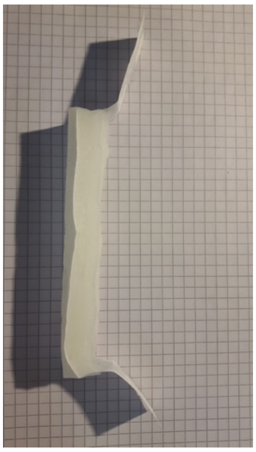


Figure 4. 14 Actuator final out of the mould

More designs

More designs were made for more experiments and more results in order to know how this actuator can help in different shapes. The above design was inspired by an octopus arm. The long and flexible arms of octopus help it to fit in different kinds of terrains and the hands are strong enough to hold on places and help in hunting for food. The mould had measurements of 10 cm from one end to another, thickness of about 2 cm and height of 1.5 cm.

Figure 4. 15 Second design actuator

4.3 Testing the specimen

Figure 4. 16 Arcada laboratory thesis table setup

The first experiment was to heat the sample with a resistance wire coiled inside it for a proper distribution of heat in the silicone. The heat was to make the ethanol bubbles inside the silicone to evaporate and expand the bubbles. The expansion of the bubbles was going to build pressure on the silicone outwards, hence making the silicone to expand. The temperature was to be measured using an infrared thermometer in order to get the exact temperature through the whole specimen. The first voltage was 1.3 V and currents 2092 mA as shown below. The sample was connected to the power source and the temperature was recorded from about 58°C to about 60°C before the resistance wire burning out before reaching the required temperature of just above 78.2°C.

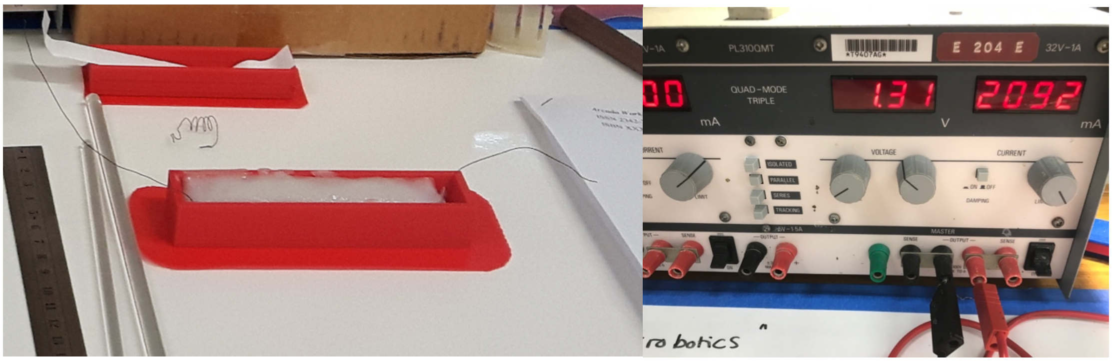


Figure 4. 17 First experiment setup

The experiment could not be continued due to the COVID-19 pandemic school lock-down. The experiment needed new moulds and resistance wire which could withstand more heat. Getting all these things ready again could have taken a lot of time and therefore a new plan was formed. The plan was to look for different ways of providing enough heat to the samples that can replace the resistance wire for the time being.

The second experiment was immersing the mould into boiling water to see if the composite will expand. The boiling water experiment was not successful since it took a long time to reach the required temperature (above 78.2° C ethanol boiling point). The other issue was that the composite could have been expanding in both directions therefore making it hard for the expansion to be noticed.

The third attempt was to put the sample into the microwave and record the temperature using the infrared thermometer as shown below.

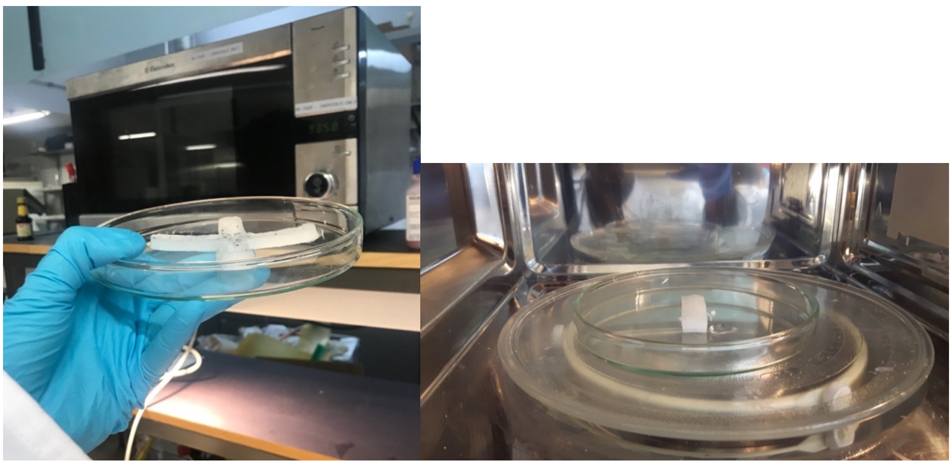


Figure 4. 18 Oven test experiment

The main aim was to get an equal distribution of heat and try to achieve the temperature just above the boiling point of ethanol (78.2°C) while keeping time in mind. The microwave method took a lot of time and there was no noticeable change of the samples and therefore another experiment was done of placing the composite (actuator) directly onto a heating plate as shown below.

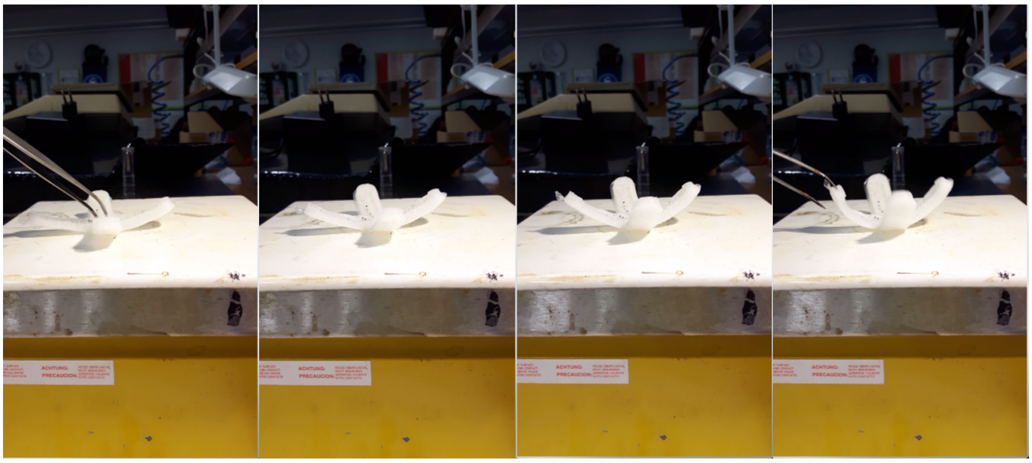


Figure 4. 19 Picture showing few second expansion (1-4seconds)

By providing temperature of 80° C on one side of the sample, the student noticed a remarkable bending of the sample towards the side where the heat was less. This showed that the ethanol bubbles were expanding really fast and with a correct heat source the experiment was going to be a success. In about 4 seconds the sample folded about 80 % of what was expected of it to fold. This was a good result and hence proved that a proper heating source is the main important thing at the moment.

4.4 Results

With a mixture of 40 % ethanol in the silicone, two specimens were obtained with clear visible ethanol bubbles in them as shown in figure 4.20 and figure 4.21 below. The micro bubbles of ethanol were the most important things in the experiment since they were to expand in order for the silicone to expand too. This was a very easy and cost-effective experiment since the bubbles formed very quickly and very visible. The size and numbers of the bubbles were to be measured and recorded but this was not done because of the previously mentioned pandemic disease.

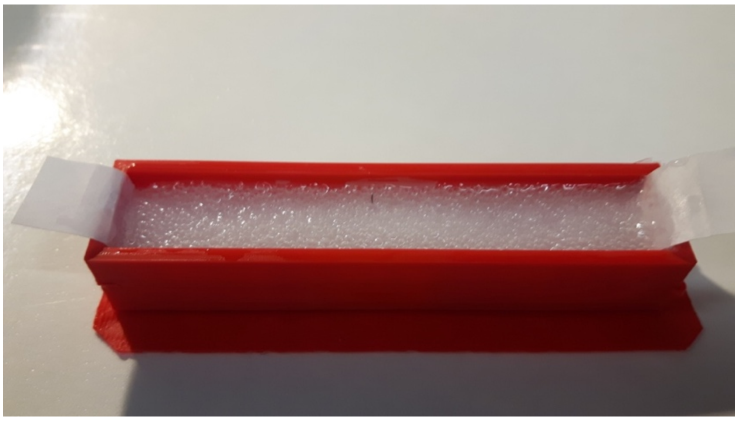


Figure 4. 20 Visible bubbles in first specimen

Figure 4. 21 Visible bubble in second specimen

The composite on the figure 4.21 managed to show visible response of heat as shown in figure 4.22 below. In about 4 seconds the silicone specimen was able to bend about 80 % of required bend upwards when it was heated as shown in figure 4.22 below on a hot plate.

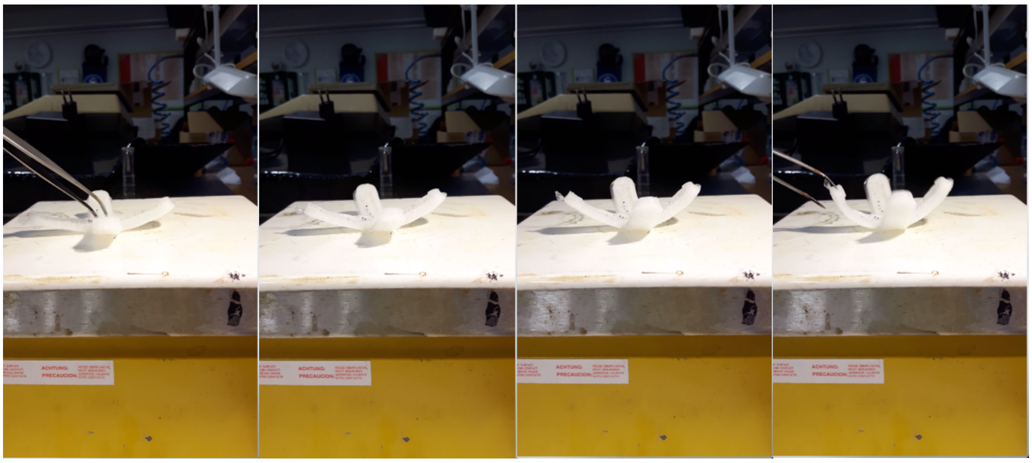


Figure 4. 22 Picture showing few second expansion (1-4seconds)

The heat was directed more on one side in order to make ethanol bubbles expand on one side inside the silicone hence forcing the specimen to bend towards the opposite side. This would make the specimen act as a gripper in a real situation. This was one the successful experiment done in that period of time.

5 PROSTHETIC AND ACTUATOR IMPLEMENTATION

5.1 Mechanical calculation

An assumption was made of hand gripping a glass of water against gravity. A list of three different weights of daily eaten food was made, in order to come up with a rough estimate of how sufficient grip force the prosthetic hand would need to provide. The following were the foods chosen.

- 0.5 litre of soda
- 100 grams of bread
- 15 grams of salad

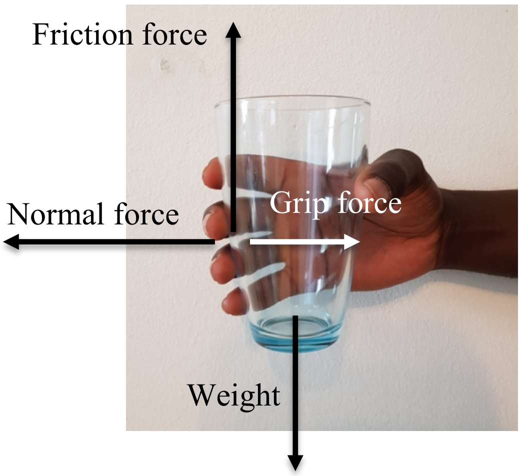


Figure 5. 1 Free body diagram

The second assumption was made that the acceleration of the cup is zero in order to neglect the weight being added by acceleration when lifting the cup. The calculations of gripping force and gripping torque was done as follows.

Vertical direction: $\sum F_y \ = Friction\ Force - Weight = 0$

Horizontal direction: $=\sum F_y \ = Gripping\ Force - Normal\ force = 0$

$f = \mu N$

Where:

$f = friction\ force$

$\mu = coefficient\ of\ friction$

$N = Normal\ force$

The minimum gripping force was calculated as follows:

Weight of the cup = m*g

Where:

m = mass of the cup

g = the Newton's constant

Mass of the cup plus the soft drink=Volume of the cup *Density = 500 ml*1.01g/ml =505 grams

(Density of regular Coca-Cola) =1.01g/ml. (Diet vs. regular Coke, 2020)

Assuming the cup and the prosthetic hand is made of plastic material:

$\mu = 0.4$ (Coefficient of friction, Rolling resistance, Air resistance, Aerodynamics, 2020)

Minimum required gripping force = m*g/ μ = 0.505 * 9.8/0.4 =13.32 N

Gripping Torque

The gripping torque was important in order to know if the actuators could be able to provide enough grip to lift the mass (Mass of the cup plus the soft drink). Gripping torque was calculated as follows.

Gripper torque: T = Required grip force * jaw length (Gripper torque formula)

Where: Jaw length (moment arm length) = face of the gripper to the center mass of the object.

In the students design the moment arm length was the radius of the cup (35 mm) and assuming that the hand will pick the cup from the top part of the cone-shaped cup.

Gripper torque= 13.32 N * 0.035m =0.4662 Nm

Therefore, the minimum required torque for each actuator for each gripping motion of each finger was calculated as shown below.

System torque/ number of fingers = 0.4662 Nm/4 = 0.117 Nm

5.2 Prosthetic Mechanism

The student decided to build a soft robotic prosthetic arm that would help people to do basic tasks like grabbing a glass of water and drinking. The prosthetic arm was to be made out of a durable plastic material, whereas the mechanical part (actuator) was going to be made of the actuator itself (silicone and ethanol) inside a metallic pump that will stand the heat from the silicone. The pump was going to be coated with silicone in order to prevent it from burning the prosthetic plastic material. Solidworks software was used in the designing of the whole prosthetic arm. Below are the step by step designs of the prosthetic.

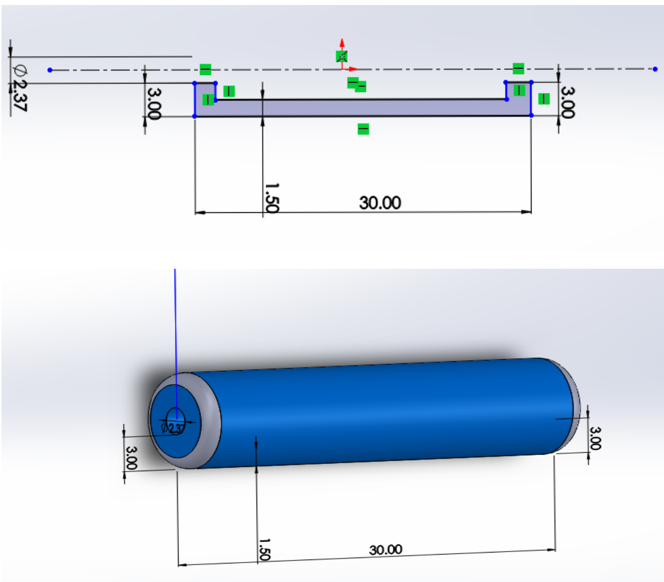


Figure 5. 2 Pump tube

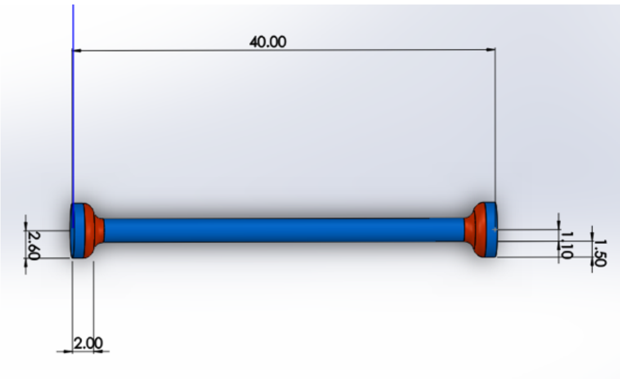


Figure 5. 3 Plastic piston.

The above pump was made in respect of the size sections of the fingers. The double-sided plastic piston was meant to push two pumps at the same time with resistance wire passing through it to the silicone and ethanol actuator placed halfway in the cylinder.

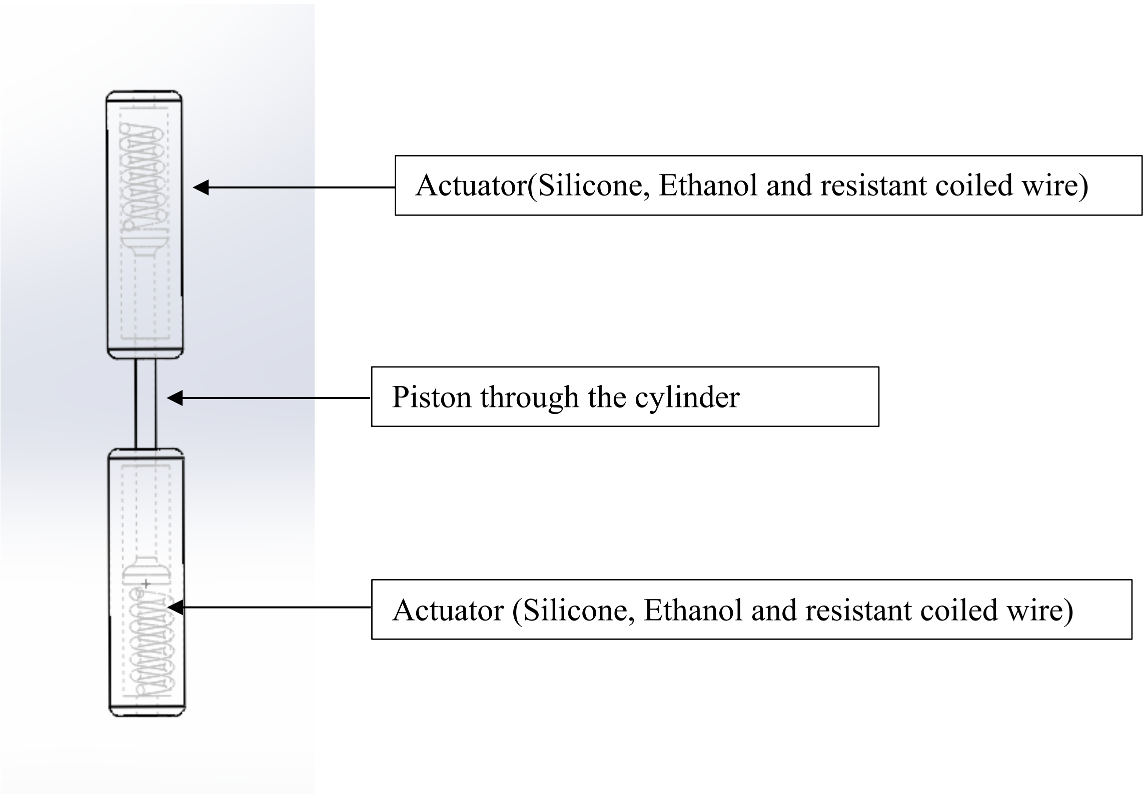


Figure 5. 4 Main mechanism setup

Prosthetic arm

The prosthetic arm was to be made of recycled plastic from waste plastic from the sea nature. These plastics were to be grinded and turned into filament that will be used for

3D printing of the prosthetic hand. Below is the normal size prosthetic hand designed with Solidworks software and later saved as an STL file ready to be 3D printed.

Fingertips

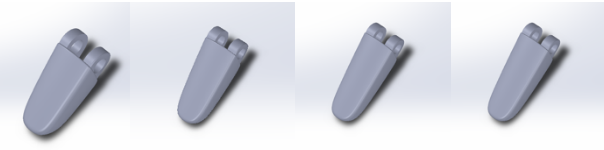


Figure 5. 5 Fingertips

Mid finger joints

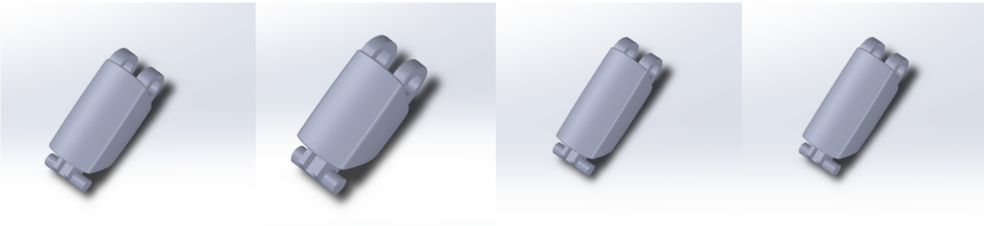


Figure 5. 6 Mid finger joints

Palm

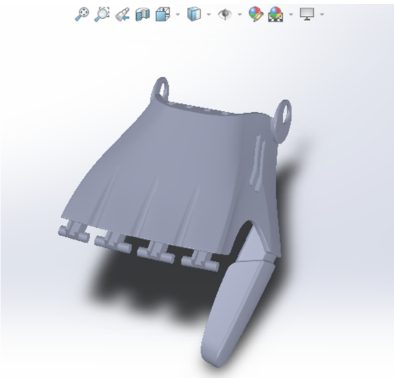


Figure 5. 7 Palm

Wrist holder

Figure 5. 8 Wrist holder

First actuators assembled parts

This was where the first actuators were to be connected to the prosthetics as shown in the figure 5.8 below.

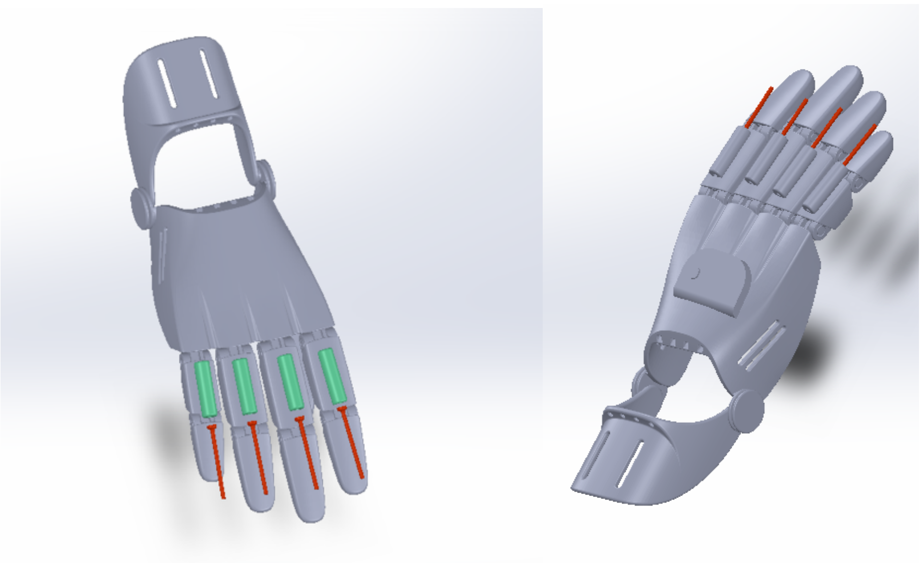


Figure 5. 9 First actuators assembled parts

Second actuator assembled part

The second assembly was to install the second actuators that would move the front part of the finger as shown in figure 5.9 below.

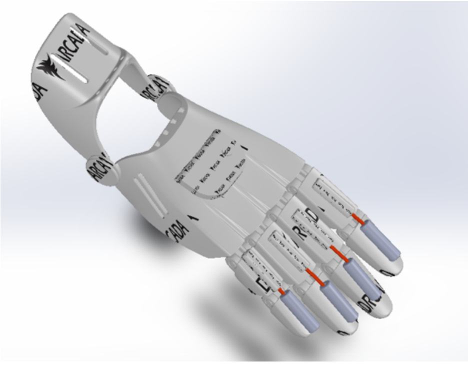


Figure 5. 10 Second actuators assembling

Final Product

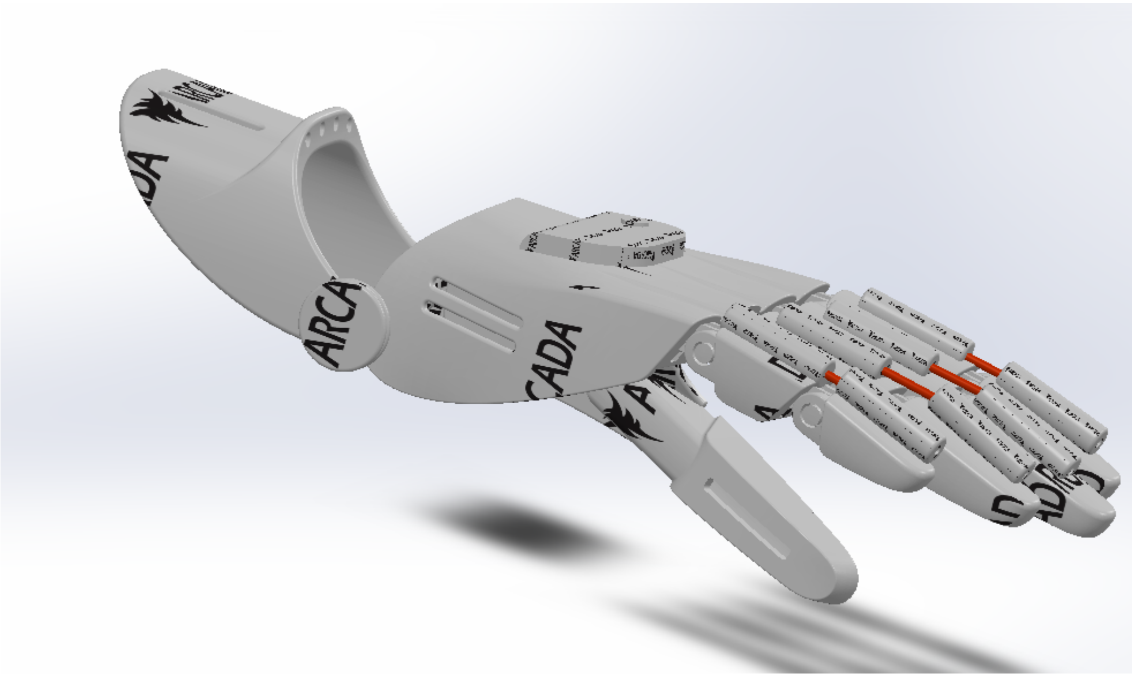


Figure 5. 11 Final product (Prosthetic arm)

6 DISCUSSION

With the limited amount of time the experiment was not completely done as required. More research on the experiment could have been done and the more experiments, the more accurate the results could have become. The other thing noticed was that the more the silicone 1520 specimen stayed exposed to air, it became harder hence losing the soft quality required of the actuator for flexible movement over a period of time. Coating the actuator would help a lot with another different material.

The other problem was that the resistance wire was not the proper required one that could withstand the heat and heat as fast as possible. This resulted in the experiment failing due to the resistance wire burning out before providing the required heat. Balancing the amount of ethanol to be used was another important thing to be done. Balancing the amount of ethanol was to make sure that there was no too much ethanol to make the specimen unsafe to use in a real situation. This would happen if too much ethanol is used, hence making the ethanol bubbles form closer to the surface of silicone and burning out easily when exposed to heat.

6.1 Potential improvements

Coating

With time, the silicone loses quality when left in open air, therefore coating the silicone with the different material was one of the options to prevent this. The other thing noticed was that, ethanol evaporate with time from the actuator and coating was the best solution for this. Coating of the actuator could have been achieved by using materials that do not allow the evaporation of ethanol through them, for example plastics like nylon.

Resistance wire

The other main issue was that it was hard finding a perfect resistant wire that can provide enough heating evenly throughout the actuator. An improvement could have been done by using perfect resistive wire as required as per previous studies that was used (NiCr) of about 10 Ω resistivity. 4 Ω (ohms) Nickel chrome resistance wire was the only one available at the moment.

More experiments

Time was another big factor to make the whole project a success. Due to the COVID-19 pandemic, the government had ordered all the schools to be closed for a period of time and hence there was no access to the laboratories or the main school. The more experiments could have done the more accurate results he could have gotten or discovered more things with the experiment.

Power supply

A good portable power supply can also improve the way forward with this experiment since the actuator will need to be moved around for other experiments to be carried on it, for example tensile testing.

7 CONCLUSION

Research was done on soft robotics and came up with idea of building a soft robot by using silicone (PDMS) and ethanol. The experiment was done in Arcada's laboratories for a limited amount of time. The experiment was a success despite different challenges along the way, for example the lack of required resistance wire and COVID-19 pandemic.

The 3D printing of the moulds was done in Arcada and printings came out very well. The experiments were not with all required steps due to the COVID-19 pandemic which led to school being closed and no access to the laboratories. Stress analysis of the specimen could have been done if the correct software was used other than Solidworks software to get a closer result. This is because the mixing of silicone and ethanol was a big challenge using Solidworks software. The other issue was the software could not really simulate the bubbles produced during the mixing of the two components.

The suggested way forward was doing the experiments manually and tests then later trying to compare with the Simulated results from the softwares for more accurate results. For further experiments, it was recommended to use COMSOL software since it is more advanced, and it can give closer results. Tensile testing can be done to the specimen to know how the mixture of the materials affect each other as specified in the thesis.

The second experiment was a success by using a hot plate which proved that this experiment could be done properly only if the whole required materials and time are available.

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