PNEUMATICALLY ACTUATED SOFT ROBOTIC PROSTHETIC HAND

A Final Year Project Report

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ABSTRACT

Conventional robotic prosthetic hands have been used for some time to give back specific functionalities to people who are either hand or arm amputees. However, these solutions are bulky, complicated, and do not reflect how a human hand would otherwise operate. As an alternative to these traditional robots, the field of soft robotics has sprung up, which utilizes soft and compliant materials to produce robots that closely mimic biological structures. A number of actuating mechanisms have been developed for this field, some of which utilize layers of hyper-elastic materials that deform and bend when subjected to pressure. Pneumatic networks (PneuNets) are one such development, which involve a hyper-elastic material with an embedded channel that can be pressurized, a series of these channels when put together undergo bending and deformation. This result has been utilized to develop prosthetic hands with fingers that closely resemble the functionality of real fingers. In this project, we have described the methodology of fabricating a soft robotic prosthetic hand using PneuNets. The goal of this project is to achieve a number of gripping states and analyze the statics and dynamics of the prosthetic hand.

ACKNOWLEDGMENTS

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ABBREVIATIONS

Pneu-Net	Pneumatic network
EMG	Electro-myography
FEA	Fluidic elastomer actuators
SDM	Shaped Deposition Manufacturing

CHAPTER 1: INTRODUCTION

1.1 Motivation

One of the most important aspects of life, for every human being, is the ability to use our hands to achieve various objectives. Our hands are the source of useful interaction with all the other objects and human beings in the world. We use our hands to operate our vehicles, our mobile phones, to drink water, to eat food, to put on clothes – in essence, it can be argued that we need hands in order to sustain ourselves and live a comfortable life. Those who, due to unfortunate circumstances, do not have hands experience a completely different dimension of life with a lot more difficulty in executing basic tasks that help us sustain ourselves, and become dependent on other human beings to help them complete those tasks.

The aforementioned unfortunate circumstances could involve traumatic injury, disease, tumors, and congenital conditions [1, 2]. These could lead to a person having to amputate their hand(s), losing the ability to perform all the functions described above. According to statistics provided by the Amputee Coalition of America (ACA), 50,000 amputations occur every year in the USA alone, and 30% of these are upper limb amputations [3]. Moreover, 41,000 people are registered for having hand or complete arm amputations [4]. According to another source, there are about 900,000 amputees in Pakistan alone. Therefore we can establish that this is a condition that affects a very large number of people in this world, altering their experience of life in a negative way.

The field of robotics has brought a solution to the market to help solve this problem – the prosthetic hand. The 'prosthesis' replaces a missing body part and is a sub-branch of rigid robotics, which deals with conventional design made of stiff components. About 60 to 70% of amputees resort to using such prosthetic limbs to restore functionality, i.e. the installed limb mimics the activity of an actual hand. Figure 1 shows a modern prosthetic hand.

Figure 1. A modern prosthetic hand used to restore functionality to hand amputees.

1.2 Problem statement

However, the reality is that while this solves a number of problems, it has insurmountable limitations. About 40 to 50% of people who utilize these prosthetic hands end up not using this solution regularly, and it is not difficult to identify why that is the case.

Figure 2 clearly exposes the situation. We can see that modern prosthetic hands are too heavy, complex, and expensive to make. They are also non-compliant, in that the surfaces that make contact do not change dynamically to even out the stress distributions. This leads to stress concentrations that either end up damaging the surfaces that are interacted with, or immobilizing the robot.

Although we use rigid materials for such robotic structures, it is clear that human bodies do not function in the same way. As humans, we are made of compliant tissues, muscles, and tendons that do not have a fixed and very high modulus of elasticity, but instead deform along with the surfaces these get into contact with to make the stress distributions uniform. Given this incongruity, there has been an increased interest in the exploration of 'soft' robotic devices. Under this umbrella term, there are a number of research directions that are being pursued. One is the testing of hyper-elastic materials that deform significantly when subjected to stress, and the use of these materials to develop actuators that mimic the movements and dynamic degrees of freedom of the biological human hands.

Figure 2. A full disassembled picture of a modern prosthetic hand showing the number of bulky parts involved, depicting a lack of human-friendly design.

1.3 Proposed solution

The field of soft robotics can offer a solution for the aforementioned problem. It can offer a design that is human-like, lighter, durable, compliant, and simple. This is because the idea of a chain of rigid links with individual dynamics for each link goes out of the window when we speak of soft robotics. A prosthetic hand that is made out of soft materials and actuated in a similar way can produce a solution that will be easy-to-use for patients, and will increase the quality and amount of functionality available.

This work, therefore, proposes the development of a novel soft pneumatically actuated robotic hand made of a hyper-elastic material that is actuated using air, i.e. when a pressure is applied to the length of actuator, it bends in a way similar to how the human hand would bend.

1.4 Project objectives

The objective of this work is to design and prototype a novel soft pneumatically actuated robotic hand that bends under the application of pressure and mimics the functionality of the human fingers. The scope of this project includes the mathematical/parametric modelling, designing, prototyping, and experimental analysis of force parameters and gripping patterns.

CHAPTER 2: LITERATURE REVIEW

To begin with, we will first go through a history of the field of soft robotics, which is relatively new and therefore, does not consist of decades of research and established practices.

2.1 Brief overview of soft robotics

Human beings have for long focused on mimicking biology in a number of ways to develop machines that utilize the way humans and animals function to produce efficient and useful devices. A significant aspect of these biological entities involves the presence of compliant and soft materials, such as the human skin, tendons, and muscles etc. Since the conventional robots are made of rigid links, they are limited in their compliance, and tend to create problems when brought into the field of human-robot interactions. In fact, their elasticity moduli are in the range of 10^9-10^{12} Pa, whereas biological tissues have moduli in the range of $10^4 – 10^9$ Pa. [5]. Therefore, several of the lessons learned from studying biological entities have produced a novel field, i.e. that of soft robotics.

This field is characterized by the use of soft, compliant materials, and actuation mechanisms that mirror biological processes. These materials can deform and absorb energy and act as continuums, instead of chains of connected links. The main problem in designing soft robots using these materials is the incorporation of sensors, actuators, and computational devices to control and direct the movements.

2.2 Dealing with actuation

Actuation is an interesting problem in the field of soft robotics, since the soft material needs a method of actuation in order to make it achieve a desired outcome. With conventional robotics, we have the use of motors as the primary source of actuation. But with soft robotics, a number of methods have come forth. One is the use of variable length tendons which are then embedded in the soft segments. Another is the use of McKibben actuators, or pneumatic artificial muscles (PAMs). These PAMs are compliant linear soft actuators composed of elastomer tubes in fiber sleeves. However, fluidic elastomer actuators (FEAs) are beginning to gain in popularity. These actuators consist of multiple layers of hyper-elastic materials which, when pressurized with gases, end up inflating and producing bending and deformations. Moreover, an advantage of this is that once these are inflated and kept at a certain pressure, these no longer need any further expense of energy and can stay locked in that position. Figure 3 shows an autonomous fish that works using this principle. The tail of the fish is made of a soft material and actuated using a FEA.

Figures 4 and 5 show this in action, with the former depicting the fish in a straight manner and the latter showing the bending and curvature of the tail, reflecting how a real life fish would swim through the water.

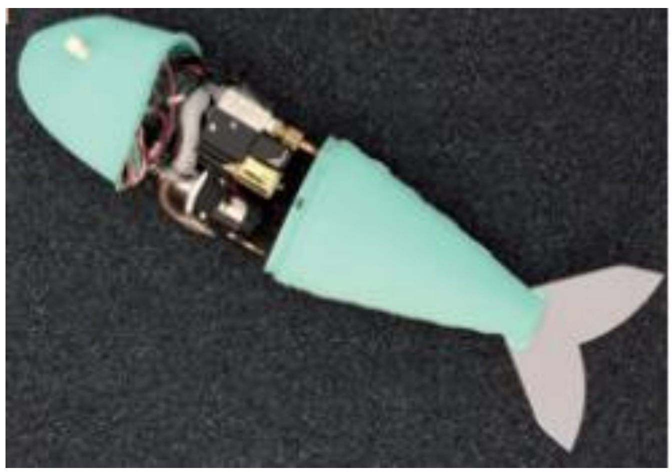

Figure 3. An autonomous fish.

Therefore, this but one example of the many ways in which various actuation mechanisms and methods are being tested out in order to copy biology in producing effective and efficient robots.

2.3 Different types of actuators

There are a number of different kinds of actuators [6], and these are described below in detail:

- Fiber-Reinforced Actuators: The fundamental structure comprises of an elastomer bladder wrapped with reinforcements that cannot be stretched. The internal bladder behaves like a balloon, expanding in all directions when inflated. Wrapping the bladder with inextensible fibers prevents it from expanding in the radial direction, therefore when inflated, it only expands in the axial direction.

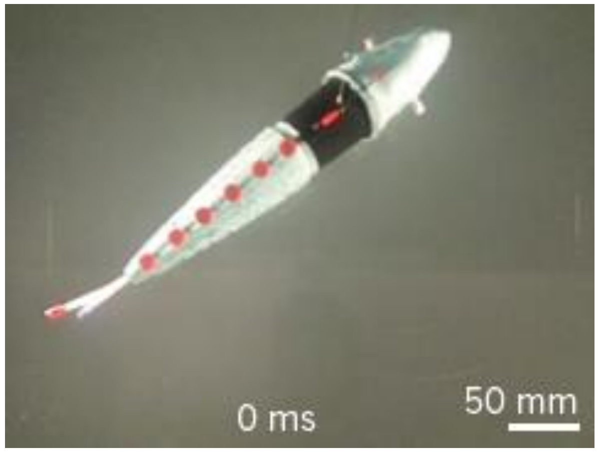

Figure 4. Fish at t = 0ms. Images are from a high-speed video of the fish executing a C turn.

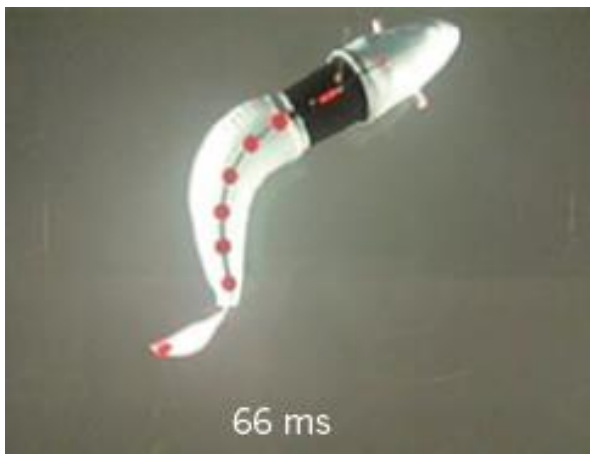

Figure 5. Fish t = 66ms. The pressurizing of the tail causes it to deform with a curvature and produce a force.

- Pneumatic Artificial Muscles: PAMs, or McKibben air muscles were invented for orthotics and come with the advantage of being rather lightweight, easy to manufacture, and resemble the human muscles by a great deal. These muscles are composed of inflatable material/bladder inside a braided mesh, which is clamped at the ends. When inflated, the braided mesh causes the bladder to expand linearly instead of in a radial direction.

Figure 6. A diagram of the structure of a pneumatic artificial muslce.

- PneuNets [7] bending actuators: These belong to a class of soft actuators originally developed at Harvard. They consist of channels arranged in series and chambers enclosed inside an elastomer. When pressurized, these channels inflate, creating deformation and bending. Through modification of the geometry of the chambers and the properties of the material walls, the nature of this motion can be controlled.

Figure 7. A Pneumatic Network (PneuNet) actuator.

There are a number of other technologies and methods developed for the actuation but these do not warrant mention at this point because they are not so widely recognized. It is pertinent to note here that in our research, we are utilizing the PneuNets framework because of its simplistic design and control schemes.

2.4 Comparison of materials

In our study, we were able to identify two main materials that are utilized in pneumatic networks. One of these is the Elastosil M4601 [8] and the Ecoflex 00-30 [9]. Table 1 presented below compares these two materials, enlisting the pros and cons and therefore giving us a basis on which to select our material.

	ECO-FLEX 00-30	ELASTOSIL M4601 A
Pros	• E = 78 KPa • More Elastic	• E = 295 KPa • Effective bending
Cons	• Less bending due to greater expansion	• Less expansion due to effective bending

Table 1. Comparative study of the two materials that can be used to make PneuNets.

From the above table, we can see that the Elastosil undergoes lesser expansion because of effective bending, and this is a useful effect for us since less expansion means less work to be done, and more bending for the same pressure is the cherry on top.

2.5 Method to pressurize actuator

We have seen from literature that there are a number of ways to actuate soft robots, however we will be focusing particularly on the PneuNets which are actuated by pressurizing them. Therefore, it is obvious that we would require some method to do the pressurizing and for this, we have three options. These options are summarized in Table 2 which offers us a good analysis and helps us in deciding which one to use.

	Compressors and Solenoid Valves	Motor with Tension Cables	Syringe-Pump Assembly
Pros	• Precision in measurement • Easily available in market	• Low Cost • Fast Response • Compact Design	• Low Cost • Light Weight • Simple Design • Energy Efficient
Cons	• Bulky • Complex • More losses • Greater Cost	• Bulky • High power requirement • Over-twist and Unwinding issues	• Not readily available • Output pressure range is smaller • Very slow actuation

Table 2. Comparative study of modes of pressurizing the actuators.

From the above table, we can see that compressors [10] are a standard method for pressure induction, but tension cables combined with motors have also been used and worked upon by researchers [11]. However, the syringe-pump [12] assembly proves to be the most suitable for our use, given all its advantages.

2.6 Modeling of hyper-elastic material

The variation of material in question with regards to our project is highly relevant in choosing the way we model our prosthetic hand. Since we will be dealing with hyper-elastic materials, convention formulas for elastic and plastic materials cannot be used to predict the behavior of our prosthetic finger under the said hydraulic pressure. The graph below shows the general response of a hyper-elastic material with respect to a Hookean solid of the same initial modulus of rigidity.

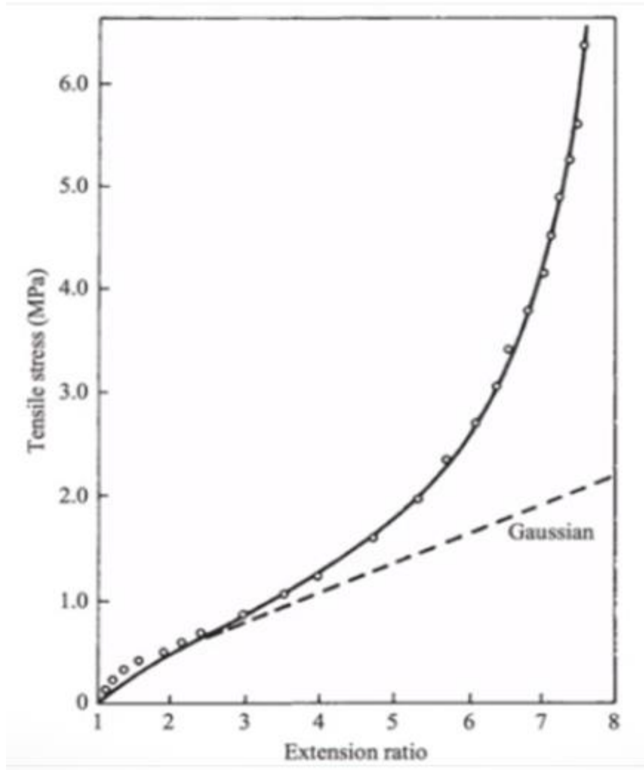

Figure 8. Graph representing the stress-strain relationship of hyper-elastic materials.

Looking at the above graph we can see that unlike conventional elastic materials, a hyper-elastic material tends to become increasingly rigid as it is extended beyond its yielding strength. This property of hyper-elastic materials is what makes it suitable for our soft prosthetic hand.

Some other properties of hyper-elastic materials include:

1. They can be stretched up to 700% of their original length without failing and deforming plastically.
2. Hyper-elastic elastomers are incompressible. They change their shape when pressurized but their volume remains constant.
3. Stress-Strain curve of hyper-elastic materials is not linear and they do not follow Hook's Law.
4. Material softens under limited tensile loads and then become stiff after further load application. They usually remain stiff under all types of compressive loads.

In finite element analysis, hyper elasticity theory is used to represent the non-linear response of hyper elastic materials at large strains. Over the years there have been many theories with regards to this model and different theories provide different results based on the shape of the hyper elastic object and the orientation of the force applied on the object. Given below is a list of some such theories.

1. Neo Hookean (1st order reduced polynomial).
2. Mooney Rivlin (1st order polynomial).
3. Yeoh (3rd order reduced polynomial).
4. 2nd order reduced polynomial.
5. 2nd order polynomial.
6. Ogden up to order 3.
7. Arruda-Boyce.

2.7 The Yeoh hyper-elastic model

For an elastic material work done is converted into the internal energy of the material (U). This energy can be related to the extension (λ) by the formula:

$$U = C(\lambda_1 + \lambda_2 + \lambda_3 - 3)$$

Here C is the initial modulus of rigidity of an object, it must be said here that for a hyper-elastic material C itself is a function of the force applied and shape of the material. The above equation is also a very simplified approximation of the Hookean model where we can see that if all the extensions along the principal axes are 0 then there will be no internal energy produced.

But for the case of our project there is only one type of motion that is expected from our robotic finger that is the bending under internal hydraulic pressure. So according to Panagiotis Polygerinos [1] we can model C as a function of a singular extension (λ) while also approximating all the extensions along the principal axes $(\lambda_1 + \lambda_2 + \lambda_3)$ with the curvature produced in the finger. So the Yeoh model equation used to predict the stress in our finger is formulated as:

$$\sigma = \frac{\lambda^4 - 1}{\lambda^3}\left(2C + 4C\left(\lambda - \frac{1}{\lambda}\right)\right)$$

Where,

$$\lambda = \emptyset / \sin(\emptyset)$$

and $\emptyset$ is the angle of curvature of the finger in question.

Stress Strain Relation:

Shown above is the Stress-Strain curve produced by a hyper elastic material where C is taken to be 150 MPa. It must be stated here that with the change of material the graph would retain its shape only if we follow the 3rd degree Yeoh model as shown previously.

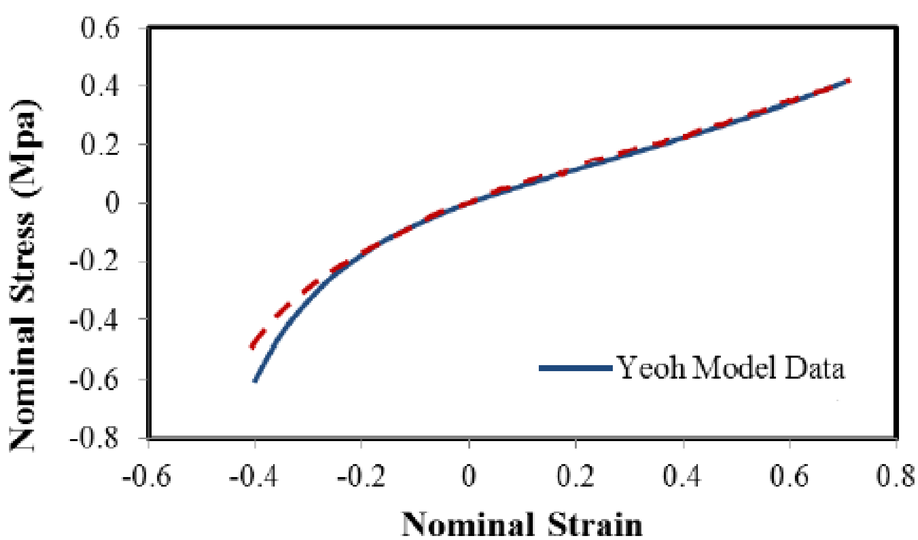

Figure 9. Theoretical stress-strain graph based on the Yeoh Model.

So now we have a stress-strain relation with respect to our desired parameter which is the bending of the material, but moving on we will show how changes in geometry are responsible for different angles being produced for the same pressures.

2.8 Cross section of a PneuNet

Shown below is the general cross-section of a robotic finger with all the changeable parameters.

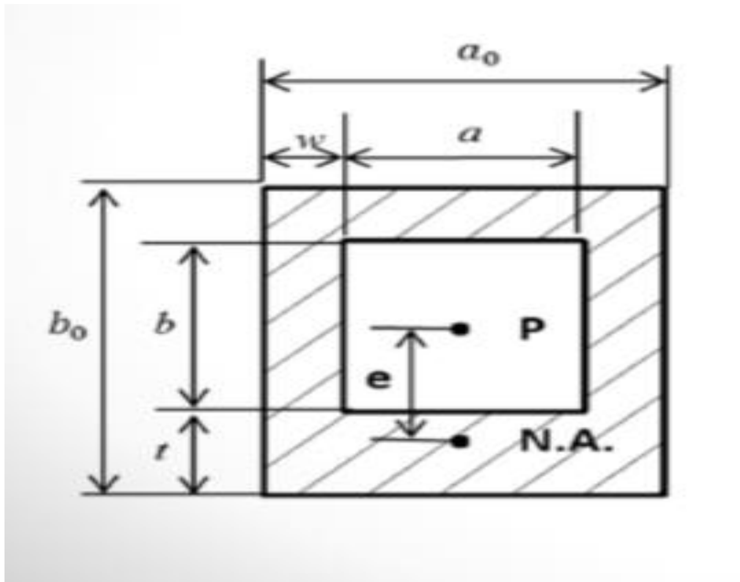

Figure 10. Description of parameters for a channel cross-section of a PneuNet.

From our knowledge of columnar bending we know that:

$$\frac{1}{R} = \frac{PAe}{EI}$$

Where,

R = Radius of curvature

P = Applied internal pressure

I = Area moment of inertia

We can see here that the curvature depends on the geometry of the cross section by e which is the distance between the centroid and the neutral axis (N.A). This distance is given with respect to the dimensions of the complete cross section as:

$$e = \frac{\frac{1}{2}a_0 b_0^2 - ab\left(t + \frac{1}{2}b\right)}{a_0 b_0 - ab}$$

From here we can see that the value e depends highly on the quantities b_0 and b which in turn depend on both the bottom layer thickness and the side wall thickness. So from this we can see that our angle of curvature depends not only on our hyper elastic model but also the internal geometry of the finger in question.

2.9 Optimization of PneuNets actuator

Weiping Hu et al [13] performed a structural optimization for the PneuNet actuator, where they utilized the Global Analysis of Variance (ANOVA) method in order to optimize the geometric parameters of the PneuNets and therefore increase the amount of bending produced for the same amount of pressure. They were able to finalize the following parameters:

- Bottom layer thickness: 4.5mm
- Wall thickness: 1.5mm
- Gap between sequential chambers: 1.5mm

Using these parameters, maximum bending was achieved for a range of pressures tested as compared to other parameters.

2.10 Research and work done on soft pneumatic hands and exoskeletons

Polygerinos et al [8] have already utilized PneuNets to develop an exoskeleton for the human hand in order to assist in grasping motions for patients who have lost some or all control over their hand movements. The experimental results from the tracking tip of the actuators demonstrated the ability to curl more than 320 degrees and to provide forces high enough to assist passive human fingers in closing i.e. impaired fingers that have some or no stiffness.

CHAPTER 3: METHODOLOGY

3.1 The design parameters

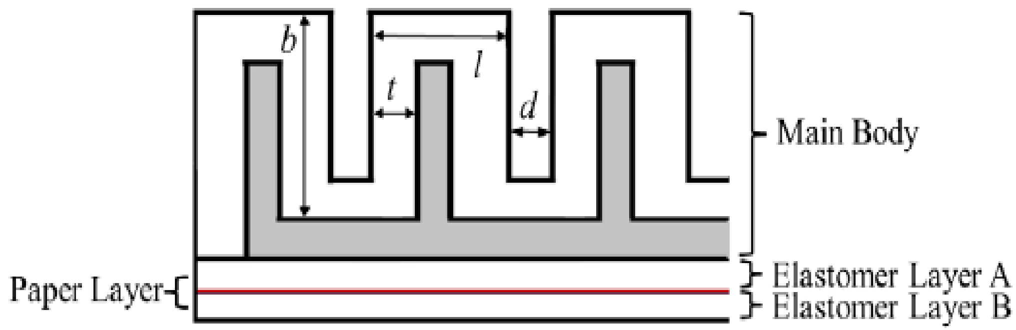

Figure 11. Dimensional parameters of lateral cross-section.

The CAD model shown above is largely based on the design shown above with the dimensions as stated.

b = 7.5 mm t = 1.35 mm

l = 6 mm d = 1.5 mm

3.2 Material used

Being a relatively new field there were not much materials available to work with in soft robotics. The only difference between soft and conventional rigid robotics is that the materials used in soft robotics are compliant and soft in touch such that they cannot cause any harm to human beings.

The material that we opted to fabricate our prosthetic hand is Elastosil M4601 A, a polymer rubber primarily composed of silicon. It is a hyper elastic material whose behavior to applied stress is non-linear and is not governed by Hook's Law. It is a soft material whose effective modulus of elasticity is determined experimentally and is given in literature to be E = 295 kPa.

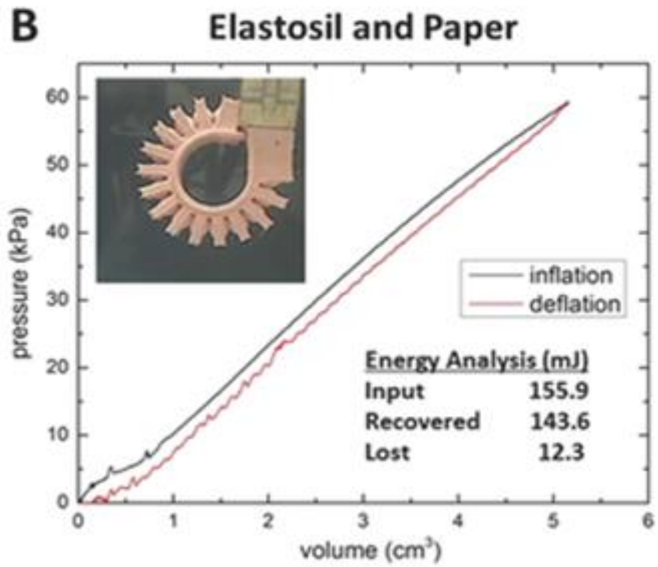

Figure 12. Expansion characteristics of Elastosil.

3.3 CAD modeling

The CAD modeling was based on the literature review and was designed to help optimize the dimensions of the actuators according to their projected usability. The internal structure was more or less set in stone after the initial literature, although it was important to structure the external ridges in a way that they allowed free bending of the actuators.

The final model is defined in the pictures given below:

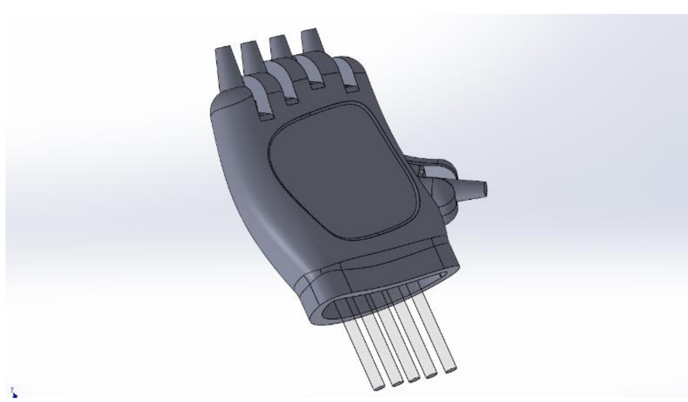

Figure 13. Initial Palm Design

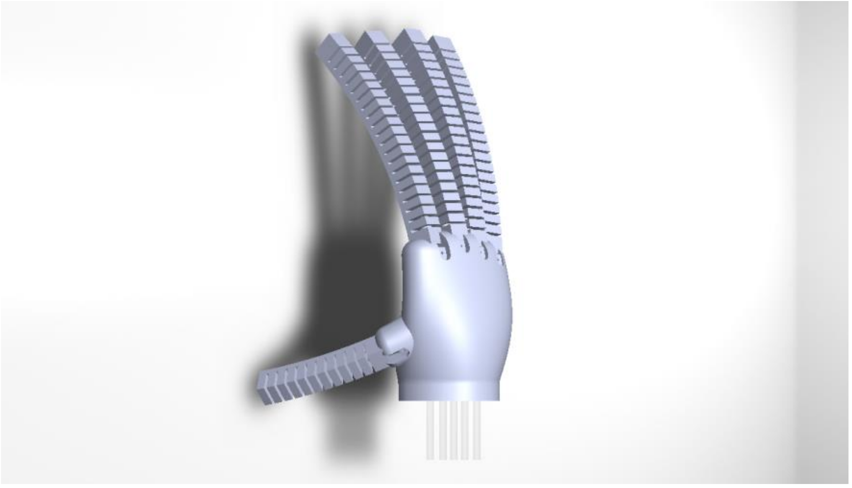

Figure 14. Complete #1

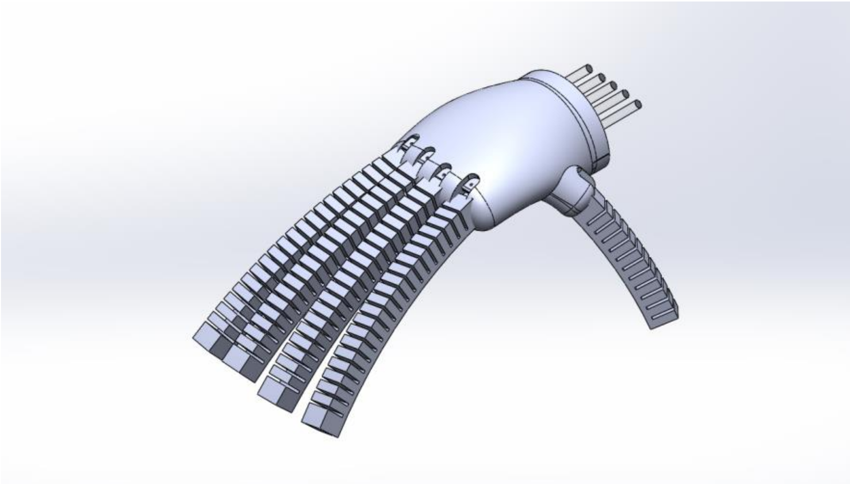

Figure 15. Complete # 2

The palm was designed keeping in mind the diameters of the pipes that had to be passed through its interior and the actuators. It had to be rigid but compliant so that it complimented the soft nature of the actuators properly and allowed a variety of grips to be achieved.

3.4 Finite element analysis

The finite element model made via Solidworks was dependent on a variety different CAD designs. These iterations of CAD designs were mostly changed on the basis of the ridge design as they hindered the transfer of fluid throughout the actuator. The behavior of the actuator under a specific range of internal pressure was tested after each iteration and the design that produced the highest amount of bending for a given pressure limit was chosen for the initial prototype. The model chosen for the FEM study was a hyper-elastic material of variable modulus of elasticity, this provided the behavior of the material under specific stress conditions.

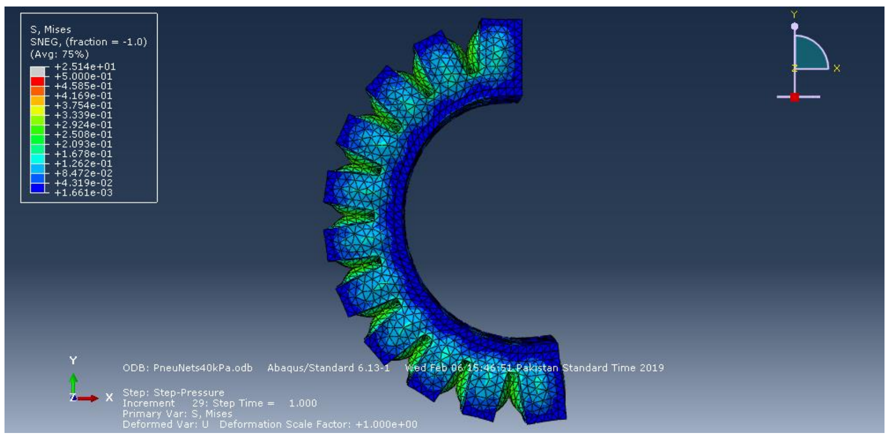

Figure 16: FEM analysis under uniform internal pressure

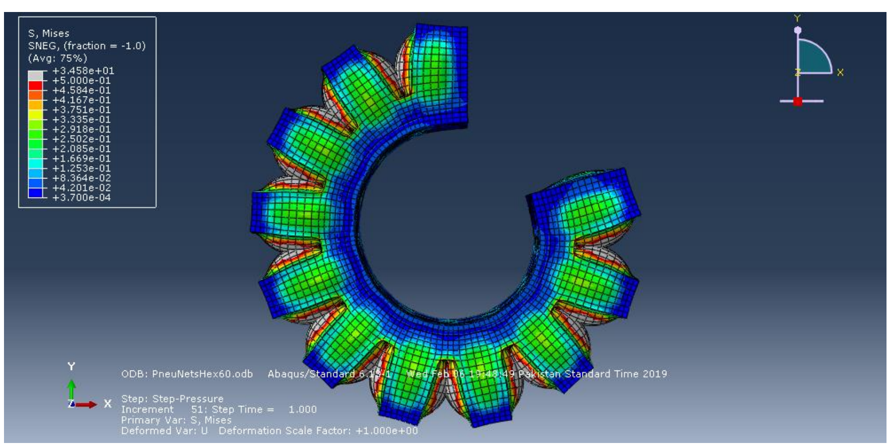

Figure 17: FEM analysis under maximum load

3.5 Manufacturing process of a PneuNets actuator

In this section we shall focus on the manufacturing process of PneuNets elastomers for a specialized five finger humanoid actuator. The salient features of the design and the internal architecture of this specific design shall be discussed later. The following are the main steps involved in the curing solid Elastosil actuators.

1. Mold design and development
2. Elastosil mixture development
3. Pouring material into mold
4. De-gassing and internal air pockets removal
5. High temperature curing
6. Extraction and bottom layer fitting

The above mentioned steps shall be discussed at length in each of their following sections.

3.5.1 Mold design and development

Through research we gained a general idea for the type of mold that was required to fulfil the specifications of our actuators. However there was still some trial and error involved in perfecting the inner ridge structure and the bottom layer thickness of the mold. Once the design was complete the mold was made using 3D printing, a hard plastic was suitable for our mold as it was required that we use the mold multiple times in order to have an abundance of actuators to choose from. Furthermore a natural locking mechanism for the upper and lower part of the mold was kept in mind while designating the tolerances for the dimensions. These two parts were designed to ‘snap’ together when applied with external pressure so that no leakage of liquid Elastosil was possible.

Figure 18. 3D printed mold designs

Shown in figure 8 are the first two designs for the molds, on the sides we can also see the natural gripers added to the design of the mold so that it can made easier to open and close the mold for multiple uses. Since this method is yet to be perfected for large scale manufacturing most of the steps required in the casting of these actuators were done manually in a specialized lab.

3.5.2 Elastosil mixture development

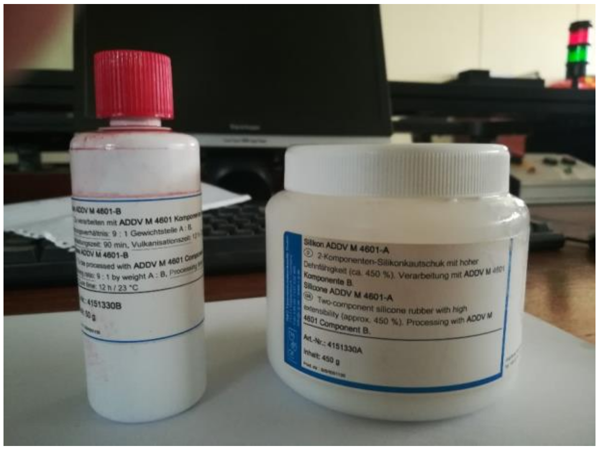

Figure 19. Elastosil sub-materials

The composition of liquid Elastosil included a stoichiometric mixture of the two products shown in Figure 9, namely:

1. Silicon ADDV-M 4601-A (Part A)
2. Silicon ADDV-M 4601-B (Part B)

The ratio with which these two parts were mixed for material development was:

$$(A)9 : 1(B)$$

by mass.

The part A consisted of the main elastomer structure in viscous liquid form while part B was added as a hardener to improve the toughness and durability of the final mixture. A simple electronic mass balance was used to make this mixture, through several trials it was found out that about 20-25 grams of this mixture was required to make one full actuator.

3.5.3 Pouring

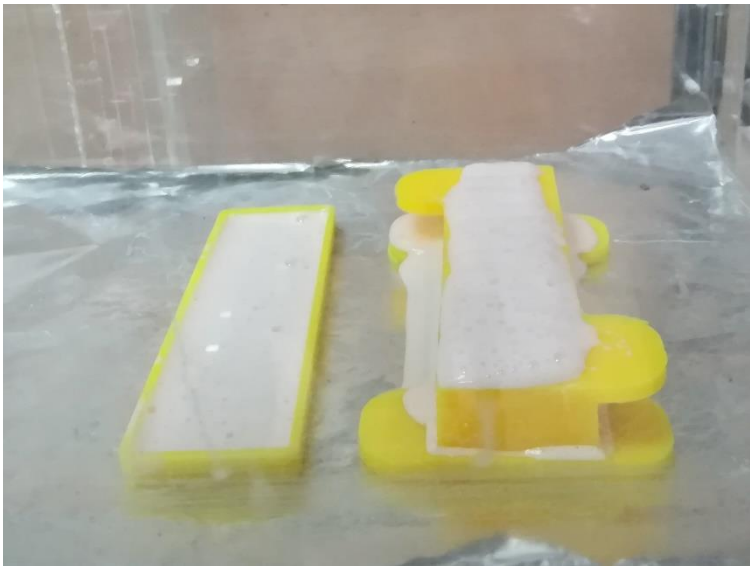

Figure 20: Mixture after being poured into the mold

A simple beaker and spatula is used to pour the final mixture on top of the upper and lower parts of the mold. Uniform pouring was kept in mind and it was made sure that each ridge chamber was filled with an equal amount of material, a little excess material was added before de-gassing to ensure that all the chambers were completely filled. Since PneuNets actuators work via the principle of internal fluid pressure there is no leverage for leakages in the final product.

3.5.4 De-gassing in a vacuum chamber

Figure 21: A pressure chamber for de-gassing

After the pouring was complete it is important to remove the internal air bubbles in the liquid before it solidifies. This is important as air pockets in the final products can make the elastomer non uniform and prone to leakages.

So, the mold was transferred to a vacuum chamber operating at a pressure of about 140 to 160 bars and kept there for 10 to 12 minutes. Due to the vacuum in the chamber, the air pockets in the mold expand and rise to the surface where they are manually popped and flattened using a spatula.

3.5.5 High temperature curing

After the mold is complete and free of air pockets it is transferred to an electric oven for curing. The general curing temperature for Elastosil is 60 to 70 degrees Celsius. The mold is kept in this environment for 10 to 15 minutes and then checked to see if the material has hardened to some degree. It is important that the consistency of the mold is not affected by the high temperature so regular watch is kept for any physical deformities that may occur during this process. After heating the mold is kept at room temperature for

3 to 4 hours to ensure that the material has solidified throughout its structure and no ridges are left empty.

3.5.6 Extraction and bottom layer fitting

Once the material has cured itself in both mold it is carefully extracted by pulling apart the locking mechanism of the mold. Since the material is elastic and tough it takes careful extraction to ensure each ridge chamber is developed properly. Once we have both the upper ridge structure and the bottom layer they are joined together using the same liquid Elastosil as a gelling material. Once these two parts are glued together it is again given 2 to 3 hours for bonding Elastosil to solidify. Finally a pipe is added to the final product, preferably just above the bottom layer to allow air to fill each internal ridge chamber and allow that actuator to bend under hyper elastic behavior.

3.5.7 Finger control

Once the model was setup and the palm-finger configuration was finalized we gained the final product that is shown below.

Figure 22: Final five finger actuator model

Each Elastosil finger was attached with a thin plastic pipe which would later be connected to solenoid valves able to regulate the pressure being supplied by the pump.

3.6 Energy conservation

The main objective of our control design was to make it as handy and portable as possible along with being reasonably robust. We needed to keep the size of the pump as small as possible this left us with the choice of only using three solenoid valves as giving individual control to each of the five fingers would put immense pressure on the pump and it would not function properly. So in order to reduce losses in pipes and make hand control more streamlined the fingers were divided into three section each controlled by a specific valve.

1. Index Finger
2. Thumb
3. Three remaining fingers (middle, ring and little)

This concise control mechanism allowed us to attain the greatest possible grip variations while keeping the pump size below the required limit. The pipes from the three remaining fingers were thus brought together and fitted into one solenoid valve which was able to provide enough pressure to fully bend three fingers simultaneously.

Figure 23: Final model with full connections

In this final model we can see the main pump airway being divided into three separate branches for each of the solenoid valves which in turn control their respective fingers.

3.7 Control mechanism

The control mechanism for the pump is simple but effective, a relay is used to regulate the current to the pump which in turn is connected to solenoid valves which regulate the pressure coming out from the pump. The pump is designed to give a constant 320 kPa of pressure which needs to be divided among five fingers. This allows each finger a pressure of 64 kPa which is more than the optimum pressure calculated through experimentation

The main control devices used are shown below:-

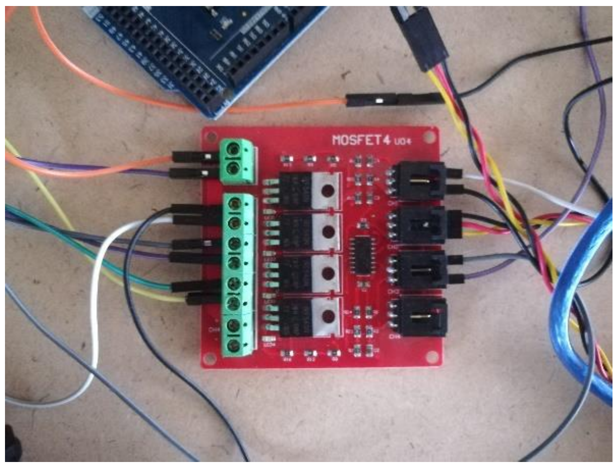

Figure 24. Four port relay

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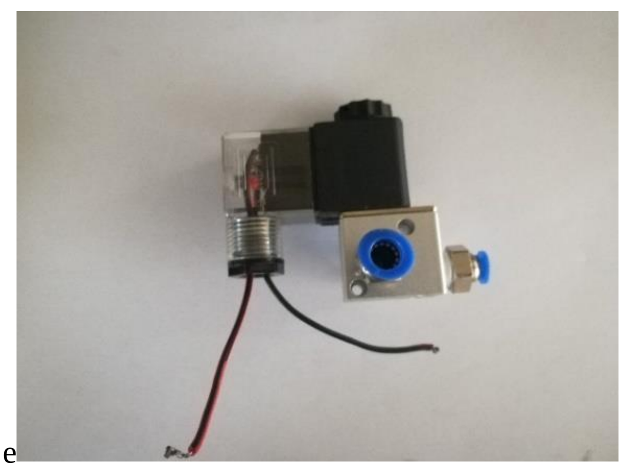

Figure 25. Solenoid Valve

Figure 26. Air pump

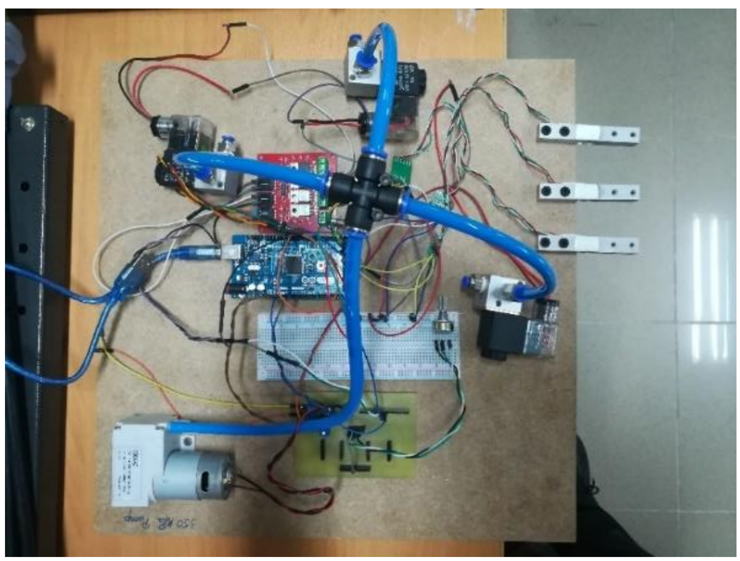

Figure 27. Complete setup

3.8 Relay control method

There were two main methods that were used for relay control throughout the experimentation of this project.

1. Potentiometer Control
2. Load Cell Control

Both of these have their own advantages and disadvantages and they both fulfil the working criteria of the project. But only one of them could be implemented in the final model. This way of choosing shall be discussed in the coming sections.

Potentiometer Control

Figure 28. Rotary potentiometer

A simple rotary potentiometer like the one shown above was connected with the relay in the first experimentation. It was successful in regulating the solenoids and gave consistent results during experiments. But since the relationship between the bending of the actuator and the applied internal pressure was not linear there were large amounts of dead zones on both sides of the potentiometer limits. Moreover the pressure release mechanism was much delayed because the potentiometer had to be manually controlled for it to be turned off. These simple reasons were why we tried out the load cell method and implemented it into the final model.

Load cell control

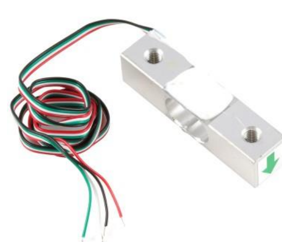

Figure 29. 5kg load cell

This is the load cell that was implemented into the final design. Three load cells were added in order to control all three configurations of the solenoid valves. One load cell controlled the index finger, another controlled the thumb and the final load cell controlled the three remaining fingers. The advantages of these load cells were that they could easily be mounted onto our experimental setup via screws and allowed better control of wire connections. Moreover they were much more responsive that the potentiometer and had almost no dead zone in the initiation. Finally it also protected the Elastosil fingers from over-pressurizing and leaking by quick breakage of circuit once the load was removed.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Finite Element Analysis

Figures 30, 31, and 32 show the bending achieved for the actuator at 40kPa (original design), 30kPa (optimized design), and 60kPa (original design) respectively. It is quite evident from the results that a pressure of 60 kPa is enough for completely curling a pneumatic actuator or finger. A comparison of finite element analysis of initial and the optimized design proved that the power requirement for improved design was much less.

Optimized parameters like wall thickness, number of ridges, shape of ridges (rectangular/round) and thickness of bottom layer were also determined with the help of finite element analysis. For each parameter a condition of minimum pressure requirement was satisfied in the optimized design. The three modes of pressure application are shown below.

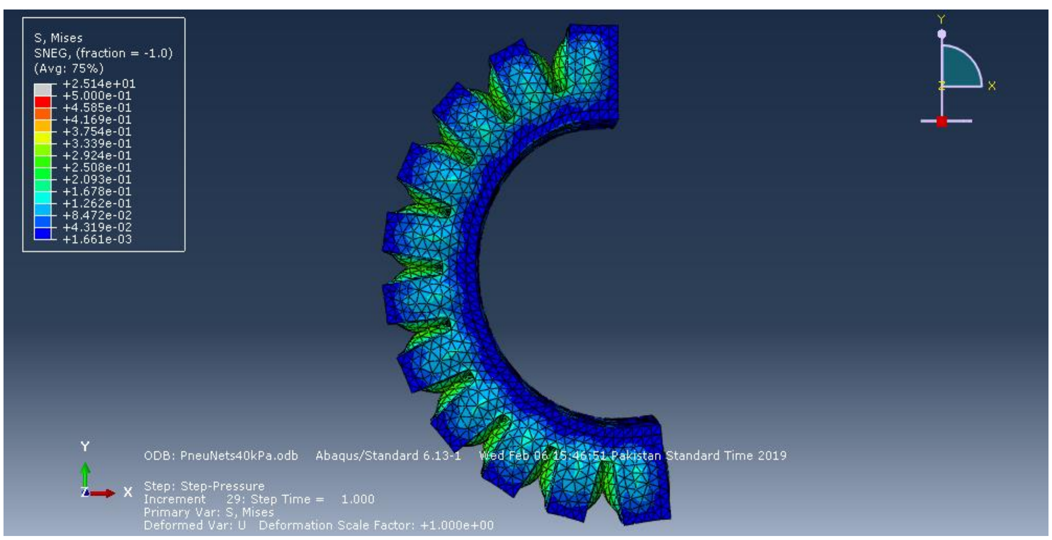

Figure 30. Original design at 40kPa

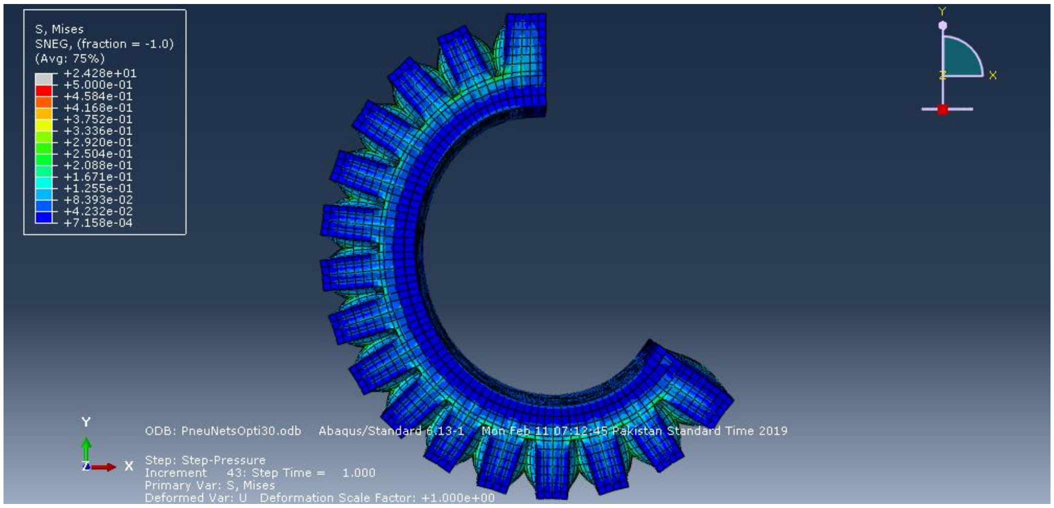

Figure 31. New design at 30kPa.

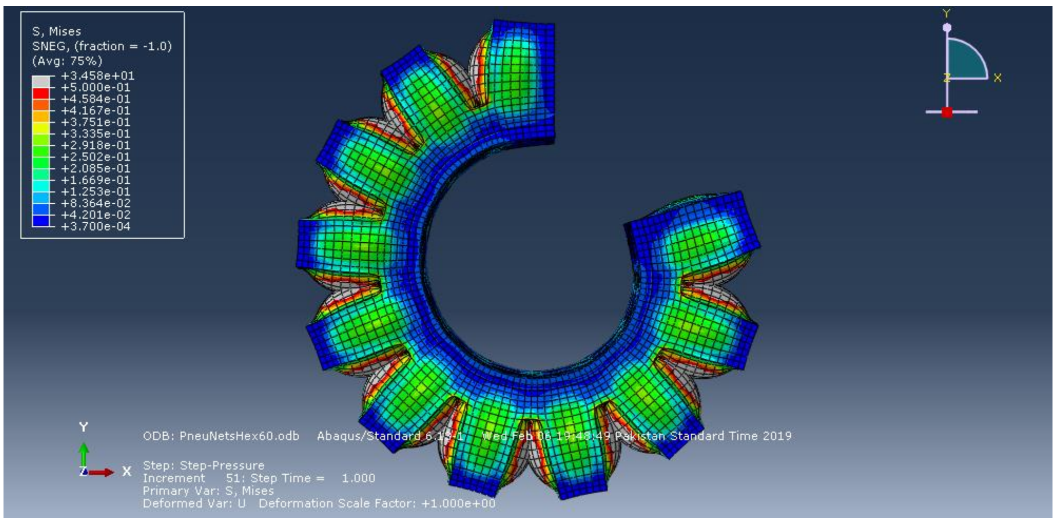

Figure 32. Old design at 60 kPa.

4.2 Fabrication of PneuNets

The fabrication process was followed as per the description given in previous section and the product that we obtained is shown below. A pneumatic finger with engraved air way inside it. A major issue in this fabrication process was that once both parts are mixed together it starts curing immediately. So pouring needs to be done as soon as possible. If it is done after a while air would not be evacuated properly and air bubbles will remain inside it. Those air bubbles then act as leakage sites.

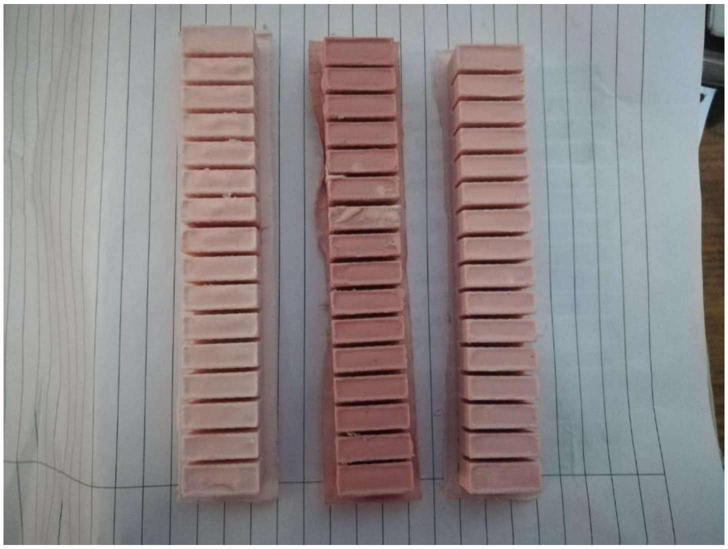

Figure 33. Fabricated PneuNets actuators.

4.3 Fabrication of complete hand

Since the idea was to keep the prosthetic hand soft so palm was also supposed to be soft. For this purpose a dish washing glove was used and its finger tips were cut off to project prosthetic fingers out of it. Small pieces of foam were shaped to form the palm of hand and pipes were projected out from the lower end. The figure below is a proof that this soft robotic hand looks like an actual human hand.

Figure 34. Completed soft prosthetic hand.

4.4 Control system

The power house of this prosthetic hand consists of a number of components. First and foremost is the 350 kPa diaphragm pump. It was custom made and delivered from a Chinese vendor. It was small in size and was powered by 12V DC supply. Then comes the network of 3 port solenoid valves operated by 12V DC. A total of three valves were used. One to operate thumb, one for the index finger and the third one for operating remaining three fingers. Since the output of pump is fixed so in order to obtain variable pressure outputs, valves were pulse width modulated. For this purpose a set of digital relays was used that delivers output based upon a specific duty cycle. 3 load cells, one for each valve, were used to change the duty cycle. The harder a load cell was pushed greater would be the duty cycle, more pressure will be added and higher will be the gripping force. A potentiometer was also used to control the frequency of valve's opening and closing. All these components were programmed and controlled with an Arduino Mega. Given below figure is a display of all components in assembly.

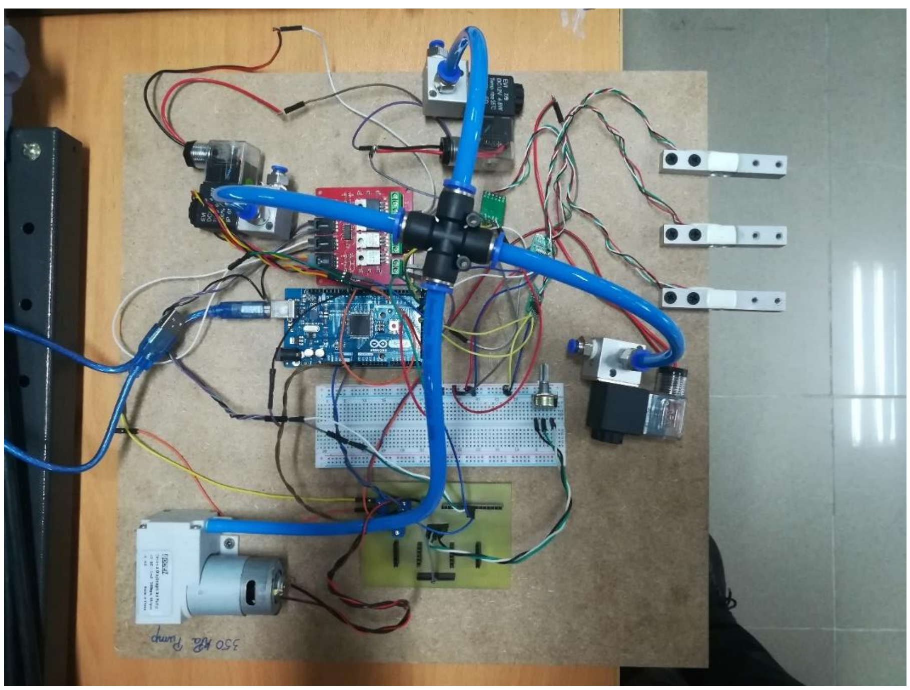

Figure 35. Complete control system used to operate the prosthetic hand.

4.5 Final assembly

Final assembly consisted of the complete hand coupled with the control system. Pipes projecting out of the hand were connected with the solenoid valves and the whole assembly became operational as a soft robotic prosthetic hand. Given below figure shows all the components (control system) mounted on a wooden board and the prosthetic hand placed beside it.

For future prospects and to make it available for amputees this assembly needs to be more compact and handy.

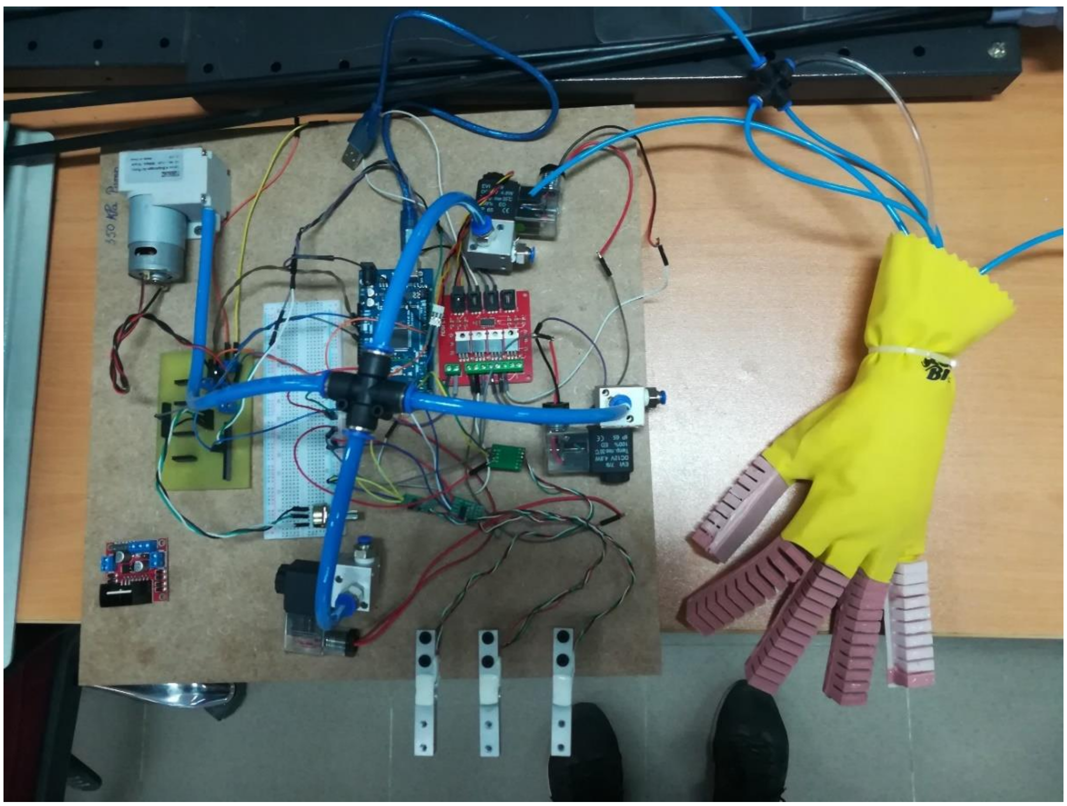

Figure 36. Final assembly of the soft robotic prosthetic hand.

4.6 Force measurement results

In order to calculate the gripping of power of each individual Elastosil finger it was important that they were setup properly and had a proper weight transfer mechanism from the tip of the finger to the newton meter.

The newton meter spring was held vertically with a string attaching the hook to the finger tip, the finger was also kept as horizontal as possible so that all of the bending weight was transferred to the tip. It is important to note here that we have assumed uniform bending of the model throughout its length and thus concluded that the tip would create the greatest gripping power.

The apparatus was set up such that the internal pressure was gradually increased via solenoid valves until a measurable extension was seen in the newton meter. The following table shows the results.

Internal Pressure (kPa)	Newton Meter Reading (N)
0	0
15	1
30	3.1
45	3.7
60	4.2
75	5.2
90	5.2

Table 3. Readings of pressure against actuator force achieved.

We can see there is a gradual increase in bending strength as we increase the internal pressure in the finger, but there is a sudden increase in bending between the 15 kPa and 30 kPa which shows the optimum working pressure for this model is somewhere close to 30 kPa. Moving on the force reading stabilizes itself once we increase the pressure above 70 kPa due to the hyper-elastic limit of the model and slight leakage of air due to high internal pressure.

4.7 Grip modes achieved

In this section we shall describe all the various grip types that were successfully achieved by our five finger actuator model. A variety of object type and hand configurations were attempted throughout the course of our experimentation and the ones that proved to be a success are shown below.

4.7.1 3 Finger oblique grip

In this situation a light blunt object was kept between the lower three fingers and the palm of the actuator. The pump was turned on and the three fingers were activated, as shown in the picture the grip was a success as the fingers wrapped themselves around the object and held it firmly with the support from the palm.

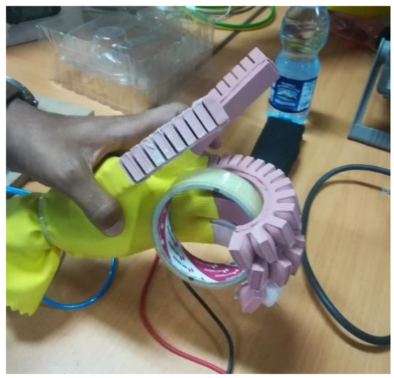

Figure 37. 3 finger oblique grip.

4.7.2 Single finger oblique grip

Here we can see the interaction between one finger, the palm and a blunt object. The object was placed between the middle finger and the palm and was pressurized via a pump.

Figure 38: Single finger oblique grip.

4.7.3 Power grip

Figure 39: Full five finger power grip.

Finally we have the full five finger power grip which was able to lift a 20N water bottle with ease and an experimental accuracy of 90%. The finger being elastic could ‘wrap’ themselves around the shape of the object with ease, the palm also being made of a soft foam structure allowed more gripping power.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

The results are clear: we have successfully developed a soft robotic prosthetic hand that can be controlled through three load cells to grasp everyday objects. The prosthetic hand can produce a maximum grasping force of 12N, which is 4N more than what is needed for Activities of Daily Living (ADL), based on the force measurement results. Moreover, the prosthetic hand can successfully accomplish the three different types of gripping modes we set out to achieve, including the three finger oblique grip, single finger oblique grip, and the full power grip. Therefore it can be concluded that this project has achieved the objectives that it set out to achieve.

Moreover we can also conclude that this is an emerging technology and still needs a lot of maturation before it can be commercialized and before this can become a standard solution for hand and arm amputees. However, what cannot be taken away from this is that this field has shown a great deal of promise.

A number of recommendations can however be presented. The first is related to the gripping modes of human hands. According to researchers, the human hand can achieve up to thirty three different gripping modes [14]. This is a reflection of the efficiency and intricacy of the design of human hands by nature, however it is a long-term goal for the soft robotics community. In this project, we have focused on achieving three out of the thirty three gripping modes and so it can be said that functionality has been achieved in all the cases where these three types of gripping motions come into play. However, a lot more still has to be done, and efforts still need to be put in to achieve the remaining gripping modes. Therefore, this is one area we will recommend that research be done to further move towards the goal of a soft robotic hand that achieves thirty three out of thirty three gripping modes.

Another area which needs work to be done is that of haptics [15]. This field studies the interactions and the sensations associated with the contact of human skin with other materials. In the context of our project, this relates to the forces and the distribution of the experienced forces when the prosthetic hand comes into contact with other objects.

Ideally, we would want the gripping force to be only as much as is required to hold the object in place appropriately, without causing too much force (and end up breaking an egg) or without producing too little force (and end up dropping the egg from its grasp). Therefore this requires a proper analysis of the forces applied by the bending actuators and the installation of a control system that can monitor and regulate the forces according to requirements.

Lastly, every PneuNet needs a pressurizing device, one which can input a range of pressures and maintain it, since that is the primary mode of actuation. In this project, we have utilized a pump-valve system that can control and vary the pressure inside the fingers with the help of relays and a microcontroller. This will be utilized in a belt arrangement that the patient using the prosthetic hand will wear. Therefore, further research is needed in order to make this system a lot more user-friendly and less bulky.

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