BODY-POWERED PROSTHETIC HAND

BME-300
BIOMEDICAL ENGINEERING DESIGN -I

Advisor
Md. Kawsar Ahmed (PT)
Lecturer
Department of BME, BUET

Team Members
Tanzila Akter (201718016)
Shakib Mahmud (201718023)
Pritom Saha (201718028)

Abstract

Prosthesis embodiment, the perception of a prosthesis as part of one's body, may be an important component of functional recovery for individuals with upper limb absence [1].The majority of people with upper limb absence live in lower, or middle-income countries. The human hand contributes greatly to hand mobility, weight bearing and manipulation capabilities in healthy individuals, but both the commercial and research domains have often overlooked prosthetic hands in favor of device development [2].The available prosthetics are very costly because they are electric powered and has lots of joints. So, most of them cannot afford it and for more joint, it is very hard to grip the hand. In this study, we created a body powered prosthetic which has primarily focused on low cost body powered prosthetic, ensuring basic movements like grip motion, reduce friction to an optimum level. We primarily focus on the mechanical design (especially careful about joints) and kinematic arrangement of these systems, giving details of articulation methods and specifications where possible and keeping the design as realistic as possible so that the patient using the device doesn't feel incomplete.

Acknowledgment

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Authors

Tanzila Akter (S201718016)

Shakib Mahmud Ayon (S201718023)

Pritom Saha (S201718028)

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Introduction

The World Health Organization estimates that 30 million people are in need of prosthetic and orthotic devices. Yet more than 75 percent of developing countries do not have a prosthetics and orthotics training program in place, often leading to poorer clinical coverage of patients [1]. Despite this, body-powered prostheses have received very little attention from researchers and have seen little development since the early 20th century [2]. Upper limb prostheses can be broadly split into two categories, active and passive. Active prostheses allow the user to actively control the opening and closing of the preventor, either through mechanical linkages (known as body powered devices) or using electric motors. Where active control is required, upper-limb body-powered prostheses may be particularly suitable for those who undertake manual work and/or do not have access to reliable electricity supplies or those with limited financial resources [3]. When the contralateral shoulder is fully retracted the 'effective length' will be at its maximum, and when the shoulder is fully protracted, the 'effective length' will be at its minimum [4]. Continuing efforts in upper limb prosthetics have led to a variety of high dexterity terminal devices (TDs) that strive to imitate the function of the human hand. However, relatively little work has been done in the development of prosthetic wrists, despite the significant role the wrist plays in manipulation tasks. Recent investigations have debated whether increased dexterity of prosthetic wrists may serve amputees better than highly dexterous hands.

Background

One of the earliest records of a prosthetic hand was described in 77AD by Roman scholar Pliny the Elder in his encyclopedia *Naturalis Historia*. After losing a hand in the Second Punic War (218–201 BC), Marcus Sergius, a Roman general, received a prosthesis that enabled him to return successfully to battle. Among the most famous examples of an early hand prosthesis was the iron hand of German knight Götz von Berlichingen. After Götz lost his hand during the Siege of Landshut (circa 1505) in Bavaria, an artisan fashioned him an iron hand with digits that could be flexed and extended passively at the metacarpophalangeal (MCPJ), proximal interphalangeal (PIPJ), and distal interphalangeal joints (DIPJ), as well as the thumb interphalangeal joint (TIPJ). On strapping on the prosthesis, Götz was able to hold reins, grip weapons, and return to battle. The device was modeled as an extension of battle armor rather than a human arm and, due to its weight, needed to be attached to Götz's armor with thick leather straps [5]. The concept of an 'automatic' body-powered upper-limb prosthesis was pioneered by German dentist Peter Baliff in 1818. Using transmission of tension through leather straps, Baliff's device enabled the intact muscles of the trunk and shoulder girdle to elicit motion in a terminal device attached to the amputation stump. For the first time, an amputee was able to operate his prosthesis with fluid body motions, rather than as a distinct foreign object.

Since World War II, there has been,especially in the United States, a considerable revival of cine plastic surgery (2,14,24,26) to produce muscle tunnels capable of harnessing for the operation of artificial arms. Practically all available muscles of the arm and two major muscles of the chest (the pectoralis major and minor) have been harnessed by various means to operate arm prostheses [6].

Literature View

Neil M. Bajaj stated that review the current state of the art of in a wide variety of passive, body-powered, and active wrists from both the prosthetics industry and research community shows that very few powered wrists are available commercially, all of which are single-DOF, that multi-DOF wrist designs are most often serial chain systems, and that there seem to be opportunities for the development of body-powered wrist devices or wrists with a parallel kinematic architecture [7].

Renato Mio stated that many types and designs of 3D-printed upper-limb prostheses have been created over the last years. However, there is no consensus in the testing methodology for these devices regarding their mechanical capabilities and the comparisons authors can make are limited to their own metrics, which could be considered as a subjective approach. This work revises the existing methods for testing both the mechanical resistance and the mechanical performance or efficiency of upper-limb prostheses; specifically, the ones that are relevant for 3D-printed body-powered prostheses [8].

Motivation

In the history of human civilization, amputation of a limb is not a new phenomenon. In the times of war, in the times of the industrial revolution, and in the current age of modern society, the reasons might have changed but the phenomena have remained. With the advancement of science and technology, the design, usability, and functionality have changed, but the purpose of the device has remained the same.

We are focusing on prosthetic arms or bionic arms. This has been developed into a very common rehabilitation device already. People, who had their hands or arms amputated due to disease or accident or who were born without their hands, use the available bionic arms to fill the void. But the available prosthetics are very costly and have a lack of practical or realistic appearance.

Problem Statement

There are many prototypes and market products available for the bionic arm. And not all of them are of the same design nor ergonomics. As this product is patient-specific, the design and need of the product are determined according to that.

But all the currently available designs in the market have some flaws. They can be stated –

- To provide more degrees of freedom to a prosthetic hand, most available prosthetics have all three joints in a finger. In this way, in the finger area alone, the prosthetic has around 15 joints [9]. All these joints provide better dexterity to the hand but overall hinders the movement of the wire that controls the fingers. Also, the more the joints, the more the chance of the wire creating difficult angles. As most available prosthetic hands are wire-controlled, these angles increase the amount of effort needed to make the basic moves. So, the functionality of these devices is hindered by this friction.

- All the currently developed models don't have a realistic appearance. Rather they prioritize showcasing state-of-the-art technology.
- So, the prices for these prosthetics are way too much.

Objectives/Specific Aims

- We want to reduce the friction present in the current design so that the functionality of the device increases.
- We also want to keep the design as realistic as possible so that the patient using the device doesn’t feel incomplete.
- Above all our main goal is to design a low-cost mechanical prosthetic that can be commercialized and mass people can buy it for themselves.

Design

Initial/ Preliminary Designs

There are several joints in a human hand. The metacarpophalangeal joint (MCPJ- the joint at the base of the finger), the proximal interphalangeal joint (PIPJ- the joint in the middle of the finger), distal interphalangeal joint (DIPJ- the joint closest to the fingertip) are the finger joints. The other joints of the hand are the wrist joint, elbow joint, shoulder joint. All these joints together work for a single hand movement. There are several types of movements of hands. These movements are flexion (moving the joint at the base of the thumb towards the heel of the hand), extension(moving the joint at the base of the thumb away from the heel of the hand), adduction(movement of the thumb base towards the back of the hand), abduction(movement of the thumb base away from the back of the hand).

As mentioned earlier that the goal of the project is to make a body-powered prosthetic hand that is able to hold an object. This project is targeted towards amputees from elbow joint. There are three joints in the finger. More joints mean more complexity. To reduce more complexity, the DIPJ joint of the finger is considered fixed. That means there are only two joints in the fingers of this project. The main focus of this project is only the movement of the fingers to hold an object. The project consists of three parts. They are fingers, palm, and forearm. The first part is the fingers. As mentioned earlier that to reduce complexity the fingers are divided into two parts. The DIPJ is considered fixed. For this the front side of the fingers are slightly curved. The fingers are hollowed to reduce the mass. Non-elastic wires or threads are used to control the fingers. So, a channel is made in every part of fingers for non-elastic wires or threads. There is also a restriction on the upper side of the joint to stop the unwanted rotations.

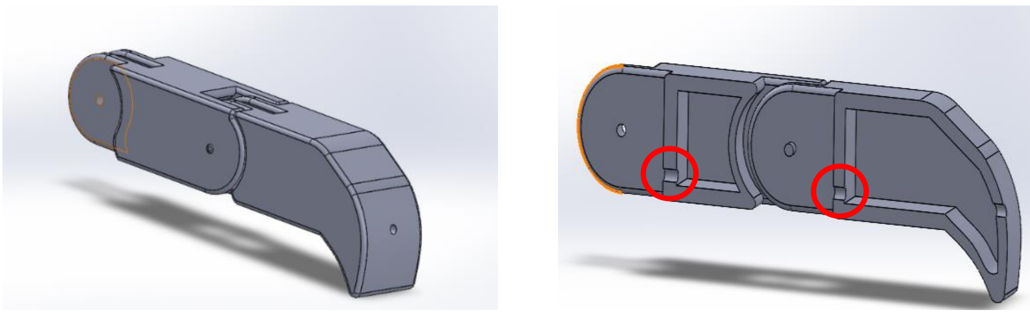


Figure 1: (a) Two-part finger; (b) Wire channel

The second part of the project is palm. The fingers are attached to the front side and the forearm is attached to the backside of the palm. There is a restriction on the upper side of joints to stop the unwanted rotations. The upper surface of the palm is made convex as the human hand. The middle of the lower surface is made concave for simple ergonomics to grab an object. For the joint of the forearm, a trapezoid shaped joint is made on the backside of the palm. The palm is hollowed to reduce the mass.

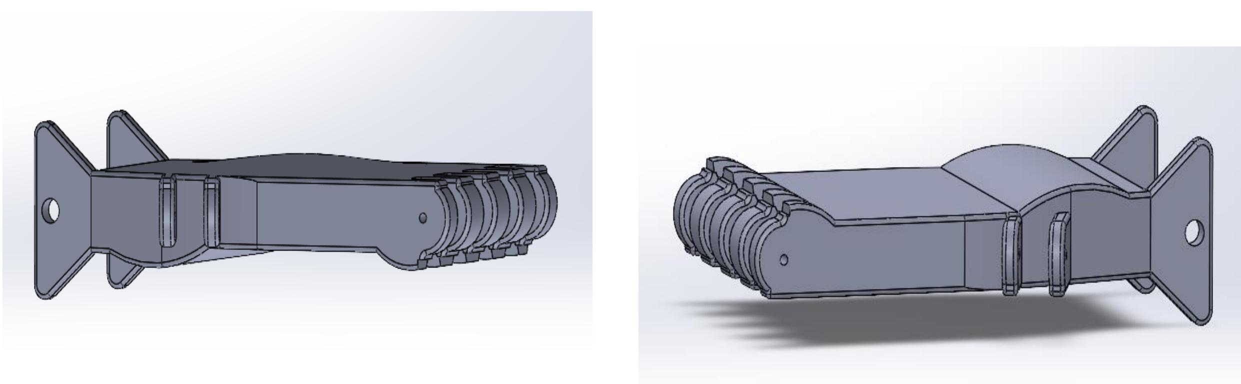


Figure 2: (a) Palm of left hand- palm faced down; (b) Palm of the left hand- palm faced up

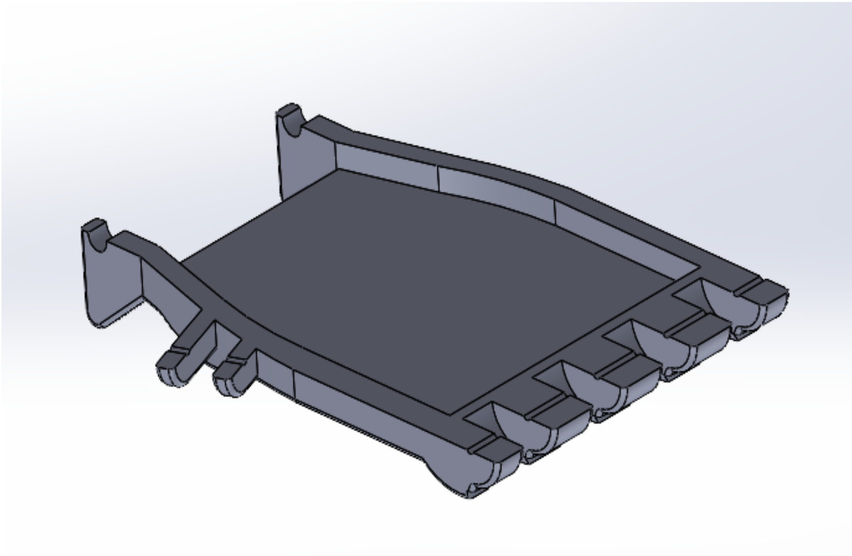


Figure 3: Palm split by a horizontal plane

The third part of the project is the forearm. The shape of the forearm is cone similar to a human hand. The connector of the forearm and the palm is square in shape. Necessary restrictions are made to stop unwanted rotations of the forearm. The forearm is hollowed to reduce the mass.

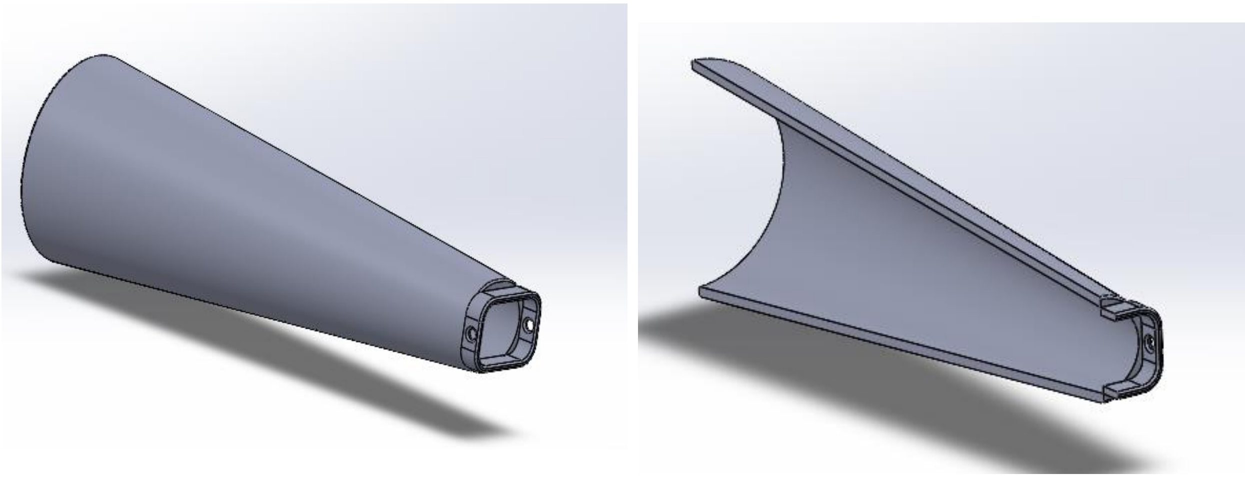


Figure 4: (a) Forearm; (b) Forearm split by a vertical plane

The non-elastic wires through the fingers all come together and form a single wire at the base of the wrist and goes through the forearm. The movement of the hand is controlled by this wire. When the wire is pulled out, the fingers of the hand are closed, and when the wires or threads are released then the fingers are back into the normal state. This mechanism is used to hold any objects by this prosthetic.

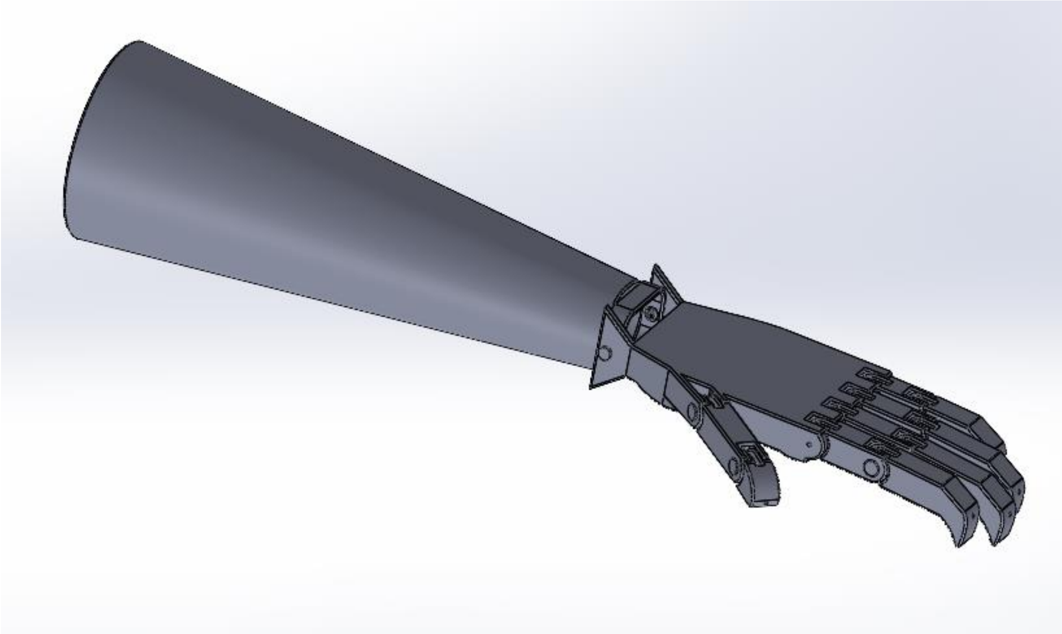


Figure 5: Full assembly of preliminary design (palm faced down)

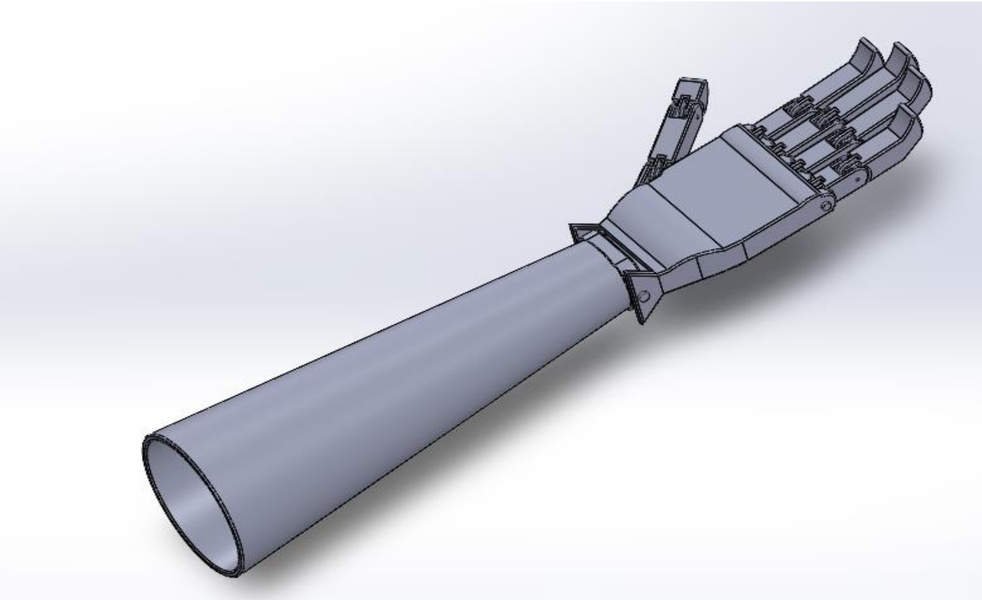


Figure 6: Full assembly of preliminary design (palm faced up)

Evaluation of Preliminary Designs

To evaluate the working performance of the initial design, a motion study had done in Solidworks. The result of motion study is:

- The index finger, middle finger, ring finger and little finger were moved well. But the problem is the fingers did not move enough to hold a small object. So, the angle of movement should be increased.
- The thumb provides support from the back of the object to the other fingers. The movement of the thumb finger should be inwards. But, in the preliminary design, the thumb finger movement was outwards. So, that means that the thumb finger was not working correctly.
- The wrist joint was incomplete too.

Final Design

To increase the angle of movement of fingers, both the two parts of the fingers are slightly cut. The angle of thumb with palm is made 90 degrees to correct the thumb movement. The size of the first part of the thumb finger is increased. To minimize the friction of the non-elastic wire, the angle of the wires has to minimize. So, the width of the base of the thumb is increased.

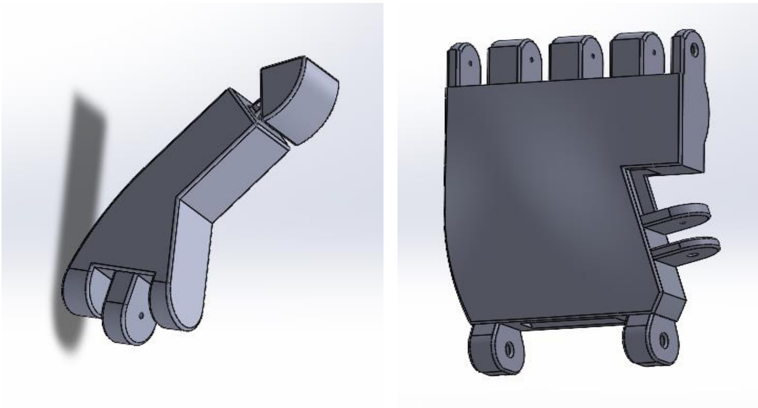
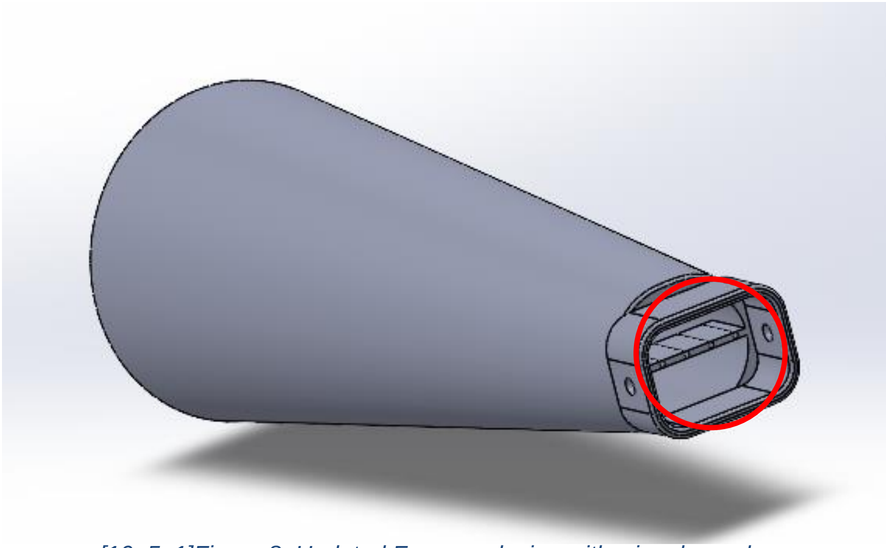


Figure 7: (a) Updated thumb design; (b) Updated Palm design

Channels for wires are created in the forearm part.



[10, 5, 1]Figure 8: Updated Forearm design with wire channels

The shoulder connector is designed. This part of the project was an addition to the preliminary design. This part connects the prosthetic to the shoulder from where the movement of the finger will be initiated.

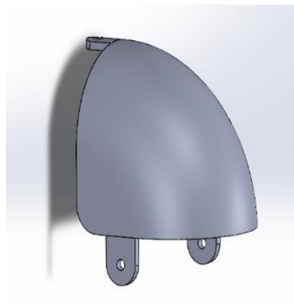


Figure 9: Shoulder connector

All the concerned parts of the prosthetic arm are designed with dimensions of human hand. So, all five fingers are different in size. This creates an illusion of a real human-like hand and also helps to properly perform the only motion it is designed for- Grabbing. As all five fingers in human hand are different in size, each finger plays different roles in grabbing an object. By distinguishing the fingers by size, each finger has different range of action. Thus, while grabbing an object, the object is held and supported in five different parts of the body of it.
Also, the dimension of the palm is also accurate as the human hand. In the forearm part, mean length of forearm of an average-sized man is used. And for the shoulder connector, as this part is just for support it will not cover the entire shoulder joint of the patient, rather it will only stay there and connect the prosthetic with the body by wires/threads.

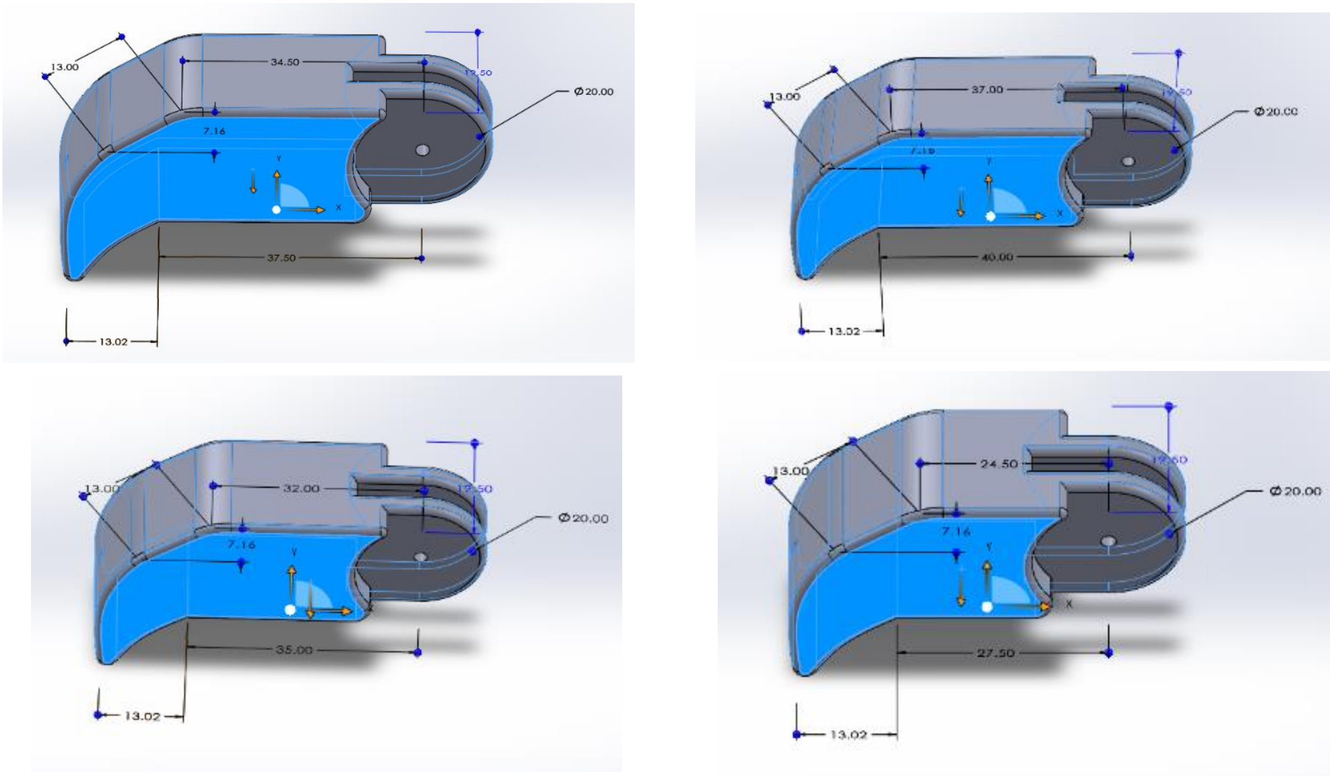


Figure 10: First part of (a) index finger, (b) middle finger, (c) ring finger, and (d) little finger with dimensions

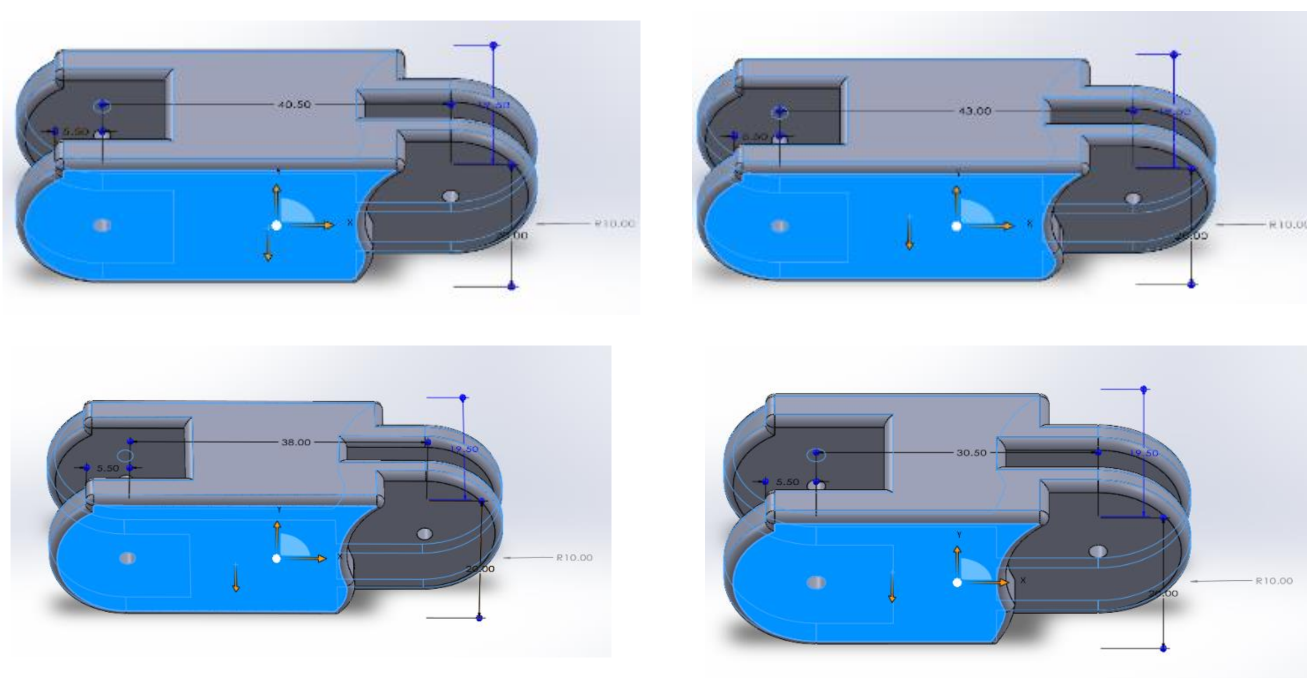


Figure 11: Second part of (a) index finger, (b) middle finger, (c) ring finger, and (d) little finger with dimensions

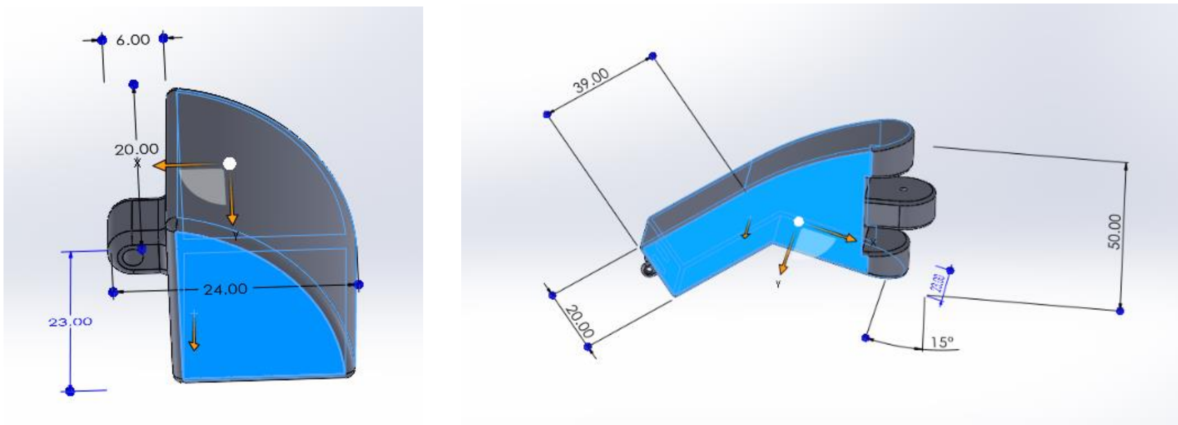


Figure 12: (a) Tip of the thumb; (b) Base of the thumb

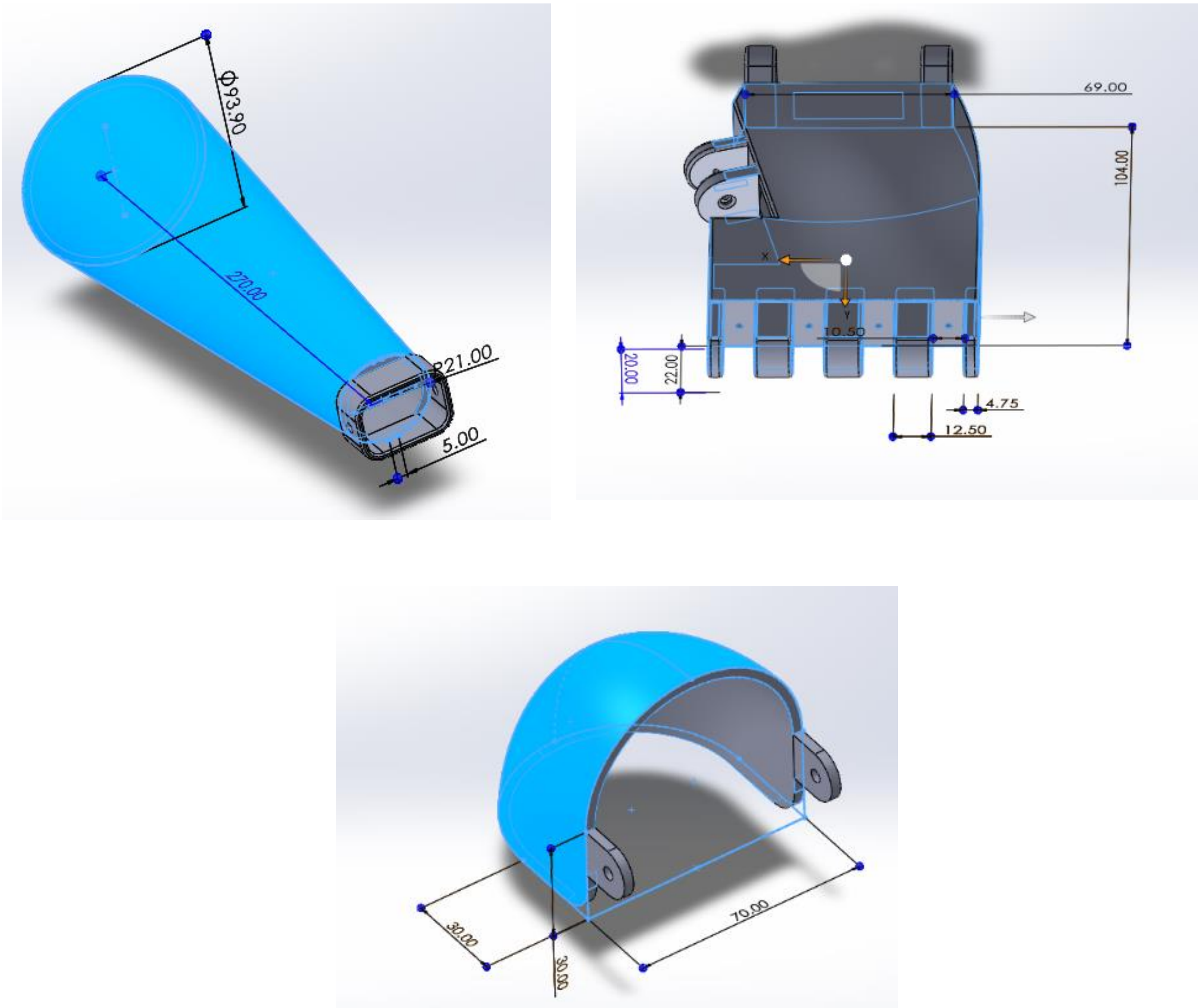


Figure 13: (a) Forearm; (b) Palm; (c) Shoulder connector

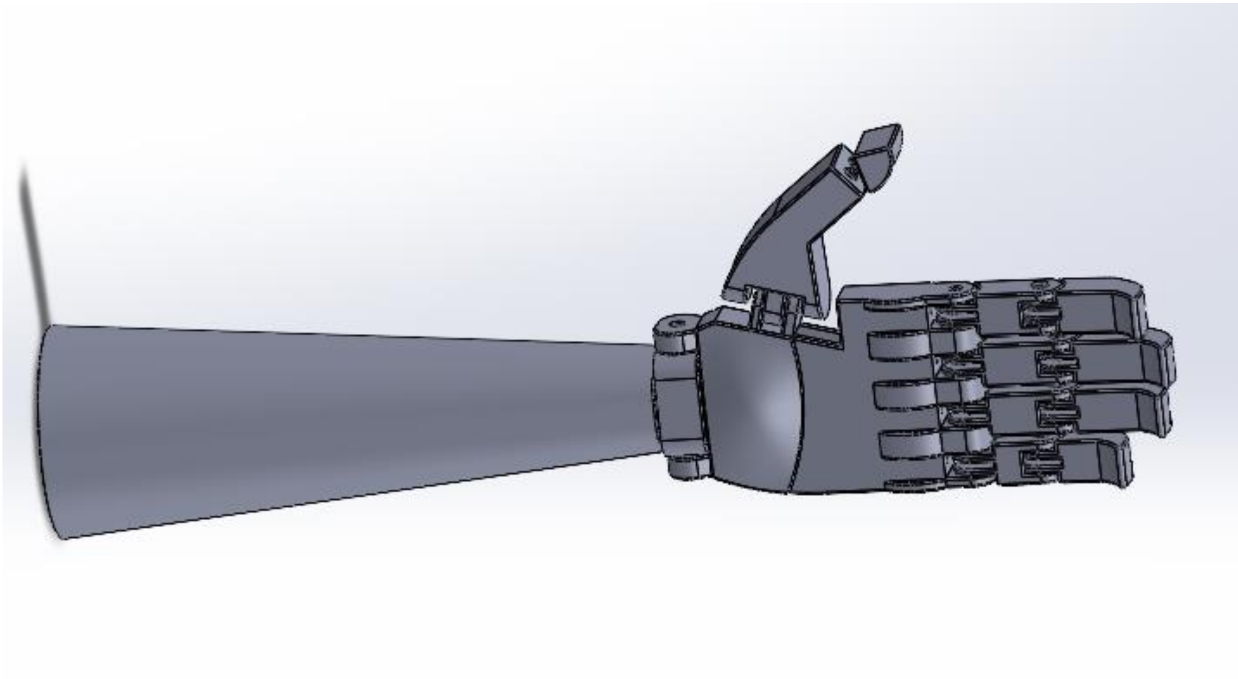


Figure 14: Fully assembled hand

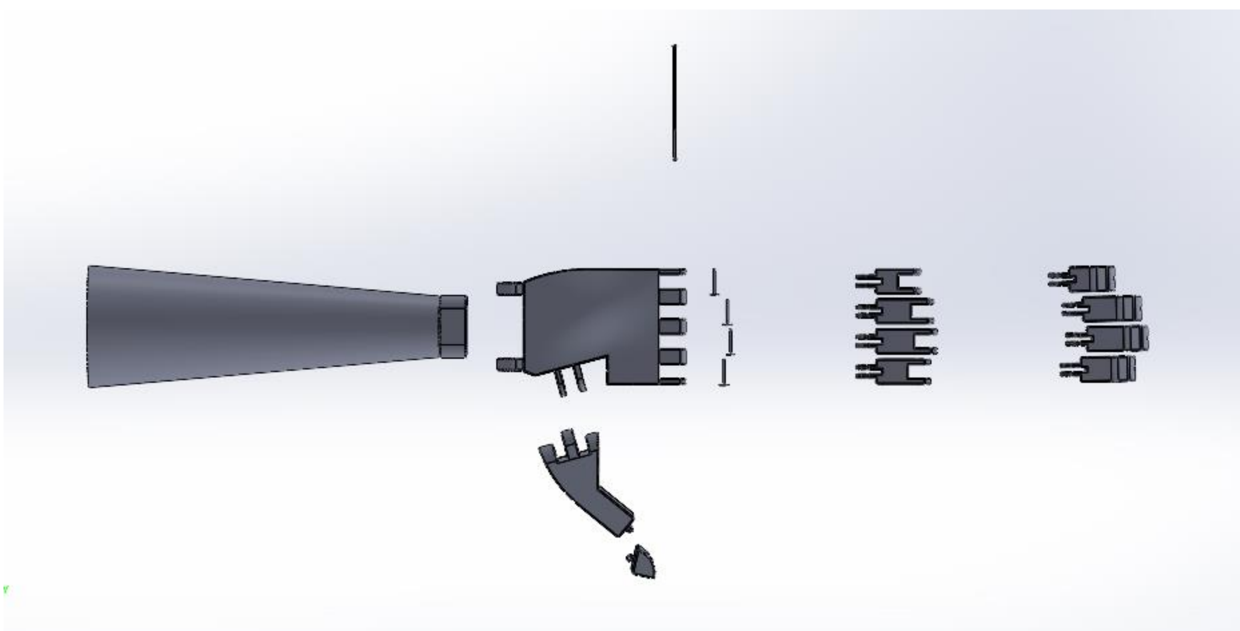


Figure 15: Fully assembled hand in exploded view

Final Design Evaluation

Methods

The methodology of the prosthetic is based on simple mechanics. The movements of fingers are controlled by non-elastic wires or threads where lever mechanism is used to the control the fingers by the wires.
Lever [11]: A lever is a simple machine made of a rigid beam and a fulcrum. The effort (input force) and load (output force) are applied to either end of the beam. The fulcrum is the point on which the beam pivots. When an effort is applied to one end of the lever, a load is applied at the other end of the lever. There are three types or classes of levers, according to where the load and effort are located with respect to the fulcrum. They are-
Class-1 lever: A Class 1 lever has the fulcrum placed between the effort and load. The movement of the load is in the opposite direction of the movement of the effort.
Class-2 lever: A Class 2 lever has the load between the effort and the fulcrum. In this type of lever, the movement of the load is in the same direction as that of the effort.
Class-3 lever: A Class 3 lever has the effort between the load and the fulcrum. Both the effort and load are in the same direction.
The class-1 lever mechanism is used to control the finger movement with the wire. Here, the fingers are the load, the wrist is the fulcrum and the muscles in arm are the efforts. The wire is connected to the tip of the fingers. So, the fingers bend at the PIPJ and the MCPJ, mimicking a grab motion of the human hand. The main objective of the prosthetic is to hold an object. The joints needed for that motion are MCPJ, PIPJ and DIPJ. The DIPJ has already been considered fixed and all the other joints are also considered fixed to reduce complexities with the wires. As the prosthetic only completes one movement, it can be seen in two different states. They are-

Resting State- In this stage there is no movement in the fingers and the all the joints are at rest.
Grab State- In this state the muscles in the arm contract and using that contraction there is a pull in the wire of the prosthetic.

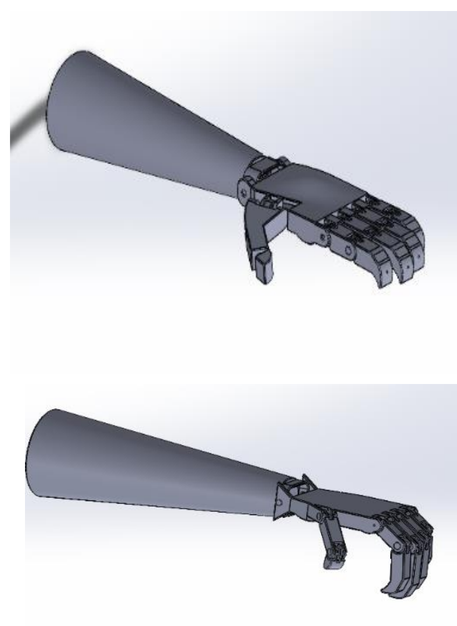


Figure 16: (a) Resting state;(b) Grab state

We considered that the hand is gripping a 20 kg object. For this, in Ansys analysis, we considered the geometry as structural steel. We created 17 bodies (forearm, palm, 5 upper finger, 5 lower finger, 5 joints between upper and lower finger). For boundary conditions, the forearm part (where the elbow starts) is considered as fixed support. In the palm, there is -196N force in the Z axis.

Results

In Ansys simulation we get a deformation result which is figured below:

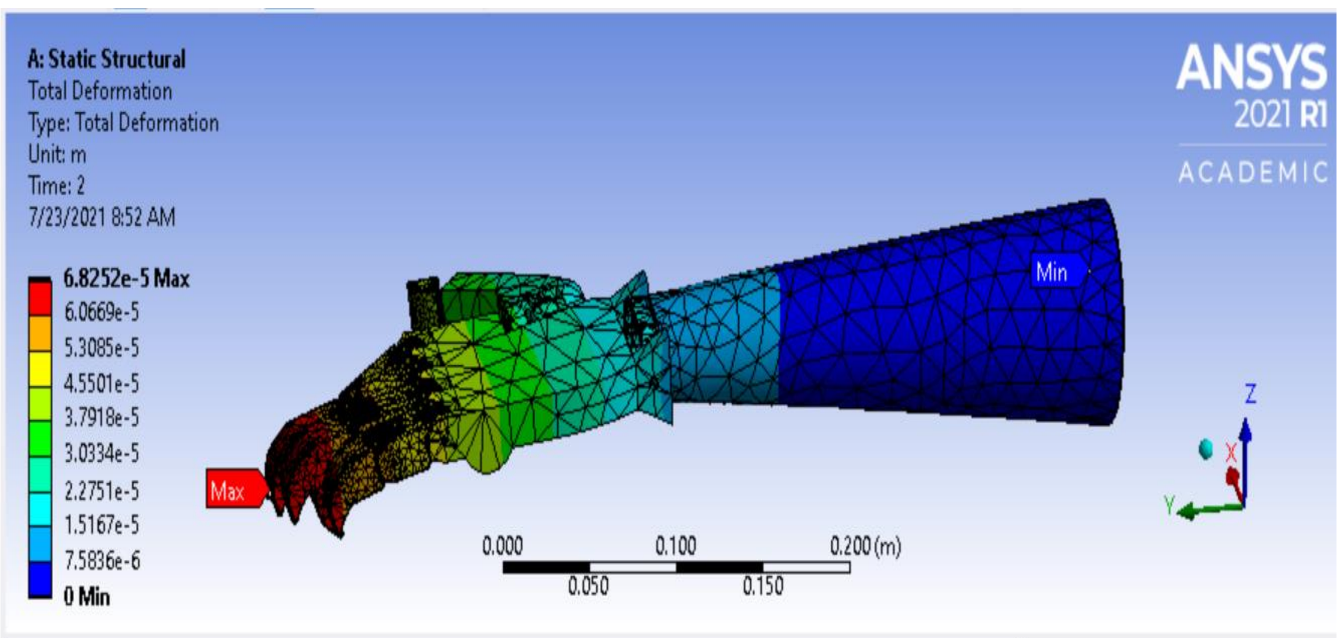


Figure 17: Total deformation simulation

And the corresponding deformation graph is:

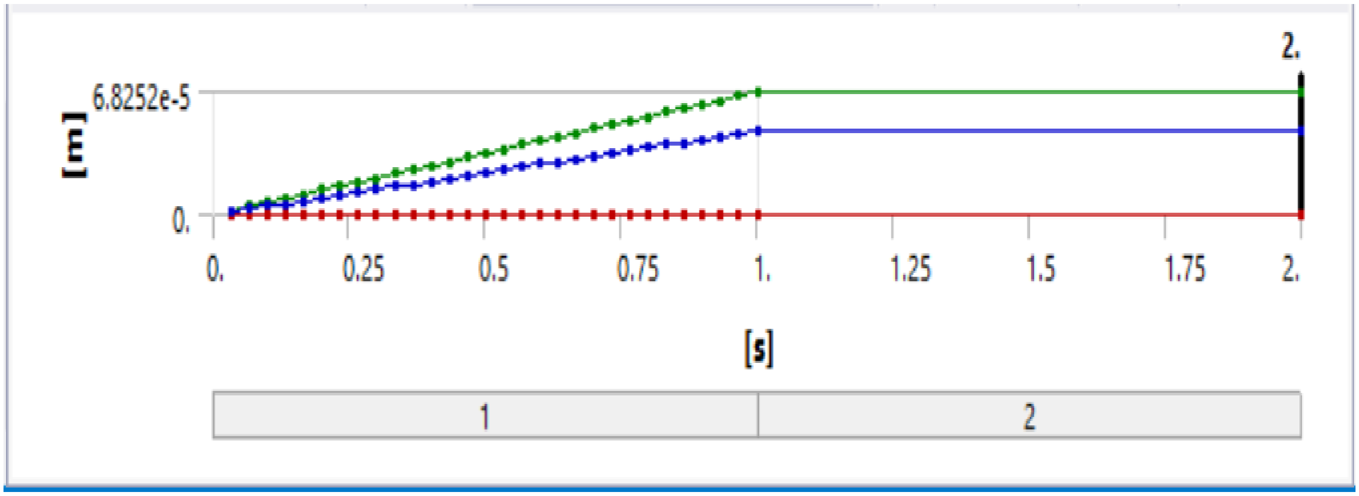


Figure 18: Deformation graph

Besides, a deformation result which is figured below:

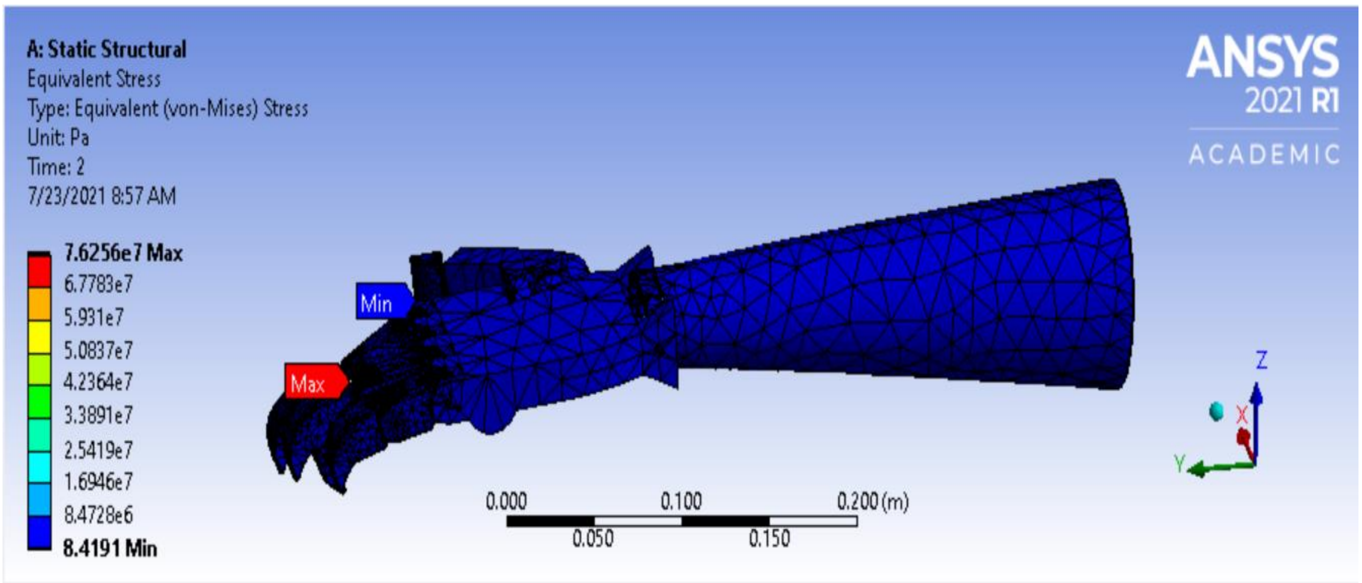


Figure 19: Equivalent stress around the prosthetic

And its’ equivalent stress graph is:

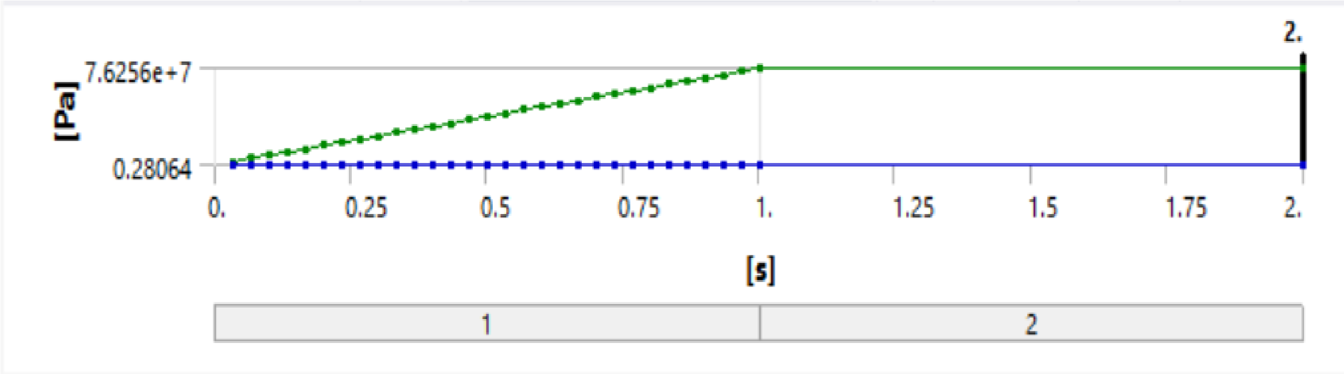


Figure 20:Equivalent stress graph

Here, there is no significant change in the stress analysis. Because the geometry is structural steel.so there is no significant change, only 196N force.

Discussion

Human prostheses are quite normal nowadays. The invention and advancement of this technology provides the amputees a ray of hope. But as the technology is improving, this artificial part is slowly becoming more human-like and for this a lot of complexities keep coming up as well and the biggest of them all is to be affordable for the general masses. Right now, a functional prosthetic hand costs more than 1000$ and if the prosthetic has more functionality then the price increases up to 100,00$ as well [12].

The objective of this project is to come up with a design that eliminates all the unnecessary functionalities and produce a prosthetic hand affordable for people here in the South-Asian sub-continent. The discussed prosthetic consists of only one motion and for that there are less complexities involved. The prosthetic can be produced by 3D printing and for that the cost of the product can be minimized.

As prosthetics are becoming more and more normal, there are lots of scope in this section of the protheses market. The technologies can be more and more improved and if, necessary research works are done in regular basis, the mechanism can be improved at lower price.

Conclusion

The project is completed in 8 weeks. In this period, the preliminary designs had been done according to a reference design of an existing 3D prosthetic hand. But in the next few weeks, the design has been modified to minimize the limitations as much as possible and maximize the functionality. This way the project design came out as a novel one fulfilling the only functionality it is designed to perform. But yes, there are both advantages and disadvantages of this design. It is unlikely to eliminate all the limitations and come up with a perfect design in such a short span of time. So, the design can be further improved and also further advantages can be achieved by modifying the design. And for that, future research on this design and the entire mechanism is needed.

Novelty of the design

- Fingers- The fingers designed here consist 2 parts where MCPJ and PIPJ are considered mobile and DIPJ is considered fixed. As the DIPJ is considered fixed, the tip of the finger is designed with a fixed bend. This helps to avoid extra complexities along with the joint and also reduces the movement of the finger which also reduces chances of unnecessary rotatory movements.
- Thumb- The thumb is not designed from the primary reference. Instead, after the first evaluation of the preliminary designs, software-based motion study was conducted to identify the problems in the design. The knowledge of the physiology of the thumb helps to understand more of its functions and the way it works. In the prosthetic, this knowledge is incorporated to come up with a human-like thumb which has a thick base and small tip. The joints in the thumb also act differently. The PIPJ of the thumb rotates at the hinge of the palm which results in a 90° rotation toward the palm and the tip of the thumb rotates along the axis of the thumb at the hinge of DIPJ.
- Shoulder Connector- This part of the project is an addition to the original reference as well. To connect the prosthetic with the patients' body, the prosthetic needs a support. This part of the prosthetic provides that support. Also, the added advantage of this connector is that this connector takes the contractions of the muscles in the arm and the contraction is then channeled to the wire which then moves linearly in a pull and relaxed state. This helps the fingers attached to the wire to move.

Pros

1. Reduced friction- In this project, one of the main objectives was to reduce friction of the entire prosthetic. If the friction is not reduced then the entire prosthetic needs a huge amount of effort to even slightly move the fingers. As the project had only one purpose, that is to grab an object, any other joints, such as- wrist joint, elbow joint, are considered to be fixed. Thus, the wire will not face any unnatural angle in its path to the tip of the fingers. For the thumb, the movement is very complex. Here, the prosthetic is designed in such a way that when the wire is pulled, the base of the thumb will articulate towards the palm but the tip of the thumb moves towards the fingers. The friction due to the angle of the thumb is very much reduced by passing the wire from the thumb through the farthest channel in the forearm.
2. Looks and ergonomics- The design of the prosthetic is completely inspired from a normal human hand. Even the dimensions are also kept the same. For this, this

prosthetic, if produced, will be closest to a natural hand so that the amputee doesn't feel incomplete.

3. Price- As the entire design is planned to manufacture a low-cost body-powered prosthetic, this project pretty much is successful. The design can be 3D printed in to different parts which can be easily assembled by anyone.

Cons

1. Functionality- As the entire project is completed through software, the real-life problems while performing the grab motion is not tested. Also, as the software simulation of the wire couldn't be made, the entire methodology of the prosthetic is in theory right now.
2. Stationary joints- To avoid complexities of the motion, few joints, such as- wrist joint, elbow joint, are considered immobile. Thus, the prosthetic cannot perform most basic hand functions. Our main target is to successfully perform the grabbing motion.

Limitations

This project is completely studied and designed by reading previous works about this topic and learning about the mechanisms in theory only. The design is also simulated in software only. So, the real-world problems are not tested. Thus, it can be said that the project is completely a theory right now. If the pandemic situation was not around, then the project could have been physically manufactured and tested on real amputees and record their experiences for further improvement. Again, as the project is simulated in software only, the main mechanism of the prosthetic couldn't be tested. The wire couldn't be simulated in Solidworks and so, the finger movement is only tested by motion study.

Future Recommendation/ Further Research

The project is successfully completed to perform only one motion in just 8 weeks. And also, as the project is entirely a theory-based design, there are lots of limitations that are discussed above. If the pandemic situation was different and the project could be made physically, then most of the limitations would have been addressed and eliminated. As that is not the case, there is still a chance of future works. In the near future, if this project is further studied the recommendation would be-

1. To study more about the mechanisms of the human hand and properties of different muscles which control hand movements.
2. To minimize friction by allowing all the joints of a human hand.
3. Study more about the thumb and its' movement. Improve the design of the thumb to get the best possible movement by also minimizing the friction due to the angle of the wire.

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