Creating a Body Powered Prosthetic Arm with 3D Printing Technology

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Abstract

3D printing, or additive manufacturing, is a technology that uses a digital model to print a three-dimensional object, layer by layer. Today, it is widely used in many different fields and provides a manufacturing method with advantages such as precision and the ability to print complex shapes from many different materials. 3D printed prostheses have recently gained a lot of interest thanks to the possibility to reduce material costs and production time. The aim of this thesis has been to create a body powered 3D printed prosthetic arm and evaluate the 3D printing technology for this purpose.

With information gathered from a thorough literature review and interviews with a patient and his prosthetist, requirements for a prosthetic arm was decided upon. The resulting design was created with inspiration from organizations providing open source 3D printed prosthetic devices. The model was designed in two different softwares from Autodesk^{TM}; Fusion 360 and Meshmixer and printed in the material Nylon PA12 in an SLS printer at the Department of Design Sciences at LTH.

The final prototype is lightweight, easily maneuvered for the user and with a simplistic design. However, many aspects still require future work to develop a fully functional prosthetic device, which is discussed in the end of the thesis. The project has shown that 3D printing is an incredible method with potential to make prostheses more customized, cheaper and produced faster. Hopefully this area will continue to grow to help more patients.

Key words: *additive manufacturing, 3D printed prostheses, upper limb prosthetic device, body powered prosthesis, amputation.*

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1 Introduction

1.1 Background

3D printing, or additive manufacturing, is a technology that uses a digital model to print a three-dimensional object, layer by layer. Today, it is widely used in many different fields and provides a customized manufacturing method with advantages such as precision and the ability to print complex shapes from a variety of materials. The use of 3D printing in the health care sector is a novel field with many possible applications, such as printing organic tissue or customized implants and orthopedic devices. 3D printed prostheses have recently caught a lot of attention, thanks to the possibilities to reduce material costs and production time. Although the 3D printing and scanning technology is available, it is not yet used clinically in orthopedic care, where most equipment provided are ordered from the bigger prosthetic companies and used with an in house created socket. The research and development of prosthetic limbs are continuously evolving and the state-of-the-art devices include neurally controlled and bone integrated prosthesis [1], [2].

However, looking at the usage of prosthetics from a bigger picture, there is an unequal distribution throughout the world. Many prosthetic devices are highly developed with expensive technical features, though not available for everyone. Especially in developing countries there is a high demand for cheap and easily manufactured artificial limbs, which is why these solutions are just as important. This is also true for amputated children all over the world who are growing rapidly and need to update their prosthetic devices at a fast rate, resulting in an expensive and often time consuming process.

1.2 Aim and purpose

The personal interest and motivation for this thesis, is taking a step back from the top end of advanced prostheses and investigate a concept and solution that could eventually reach more people and be beneficial not just to a small part of the world's amputees.

The aim of the project is to create a body powered and 3D printed prosthetic arm and evaluate the 3D printing technology for this purpose. The goal is to design a simple, yet functional transradial prosthesis, *i.e.* a prosthesis starting below the elbow. An existing method for custom made sockets based on 3D scanning will be used. The ambition is to combine the comfort of a personalized socket with a 3D printed hand and arm that can easily be maneuvered by the user.

The goal is also to reduce the need for a shoulder harness and instead design a prosthesis only controlled by the bending of the elbow. The thesis is written in association with Aktiv Ortopedteknik at Skåne University Hospital, though the focus is not to create a prosthesis that will replace the ones used in clinics today, rather explore and evaluate the possibilities of 3D printing in the prosthetic area.

2 Theory

2.1 Amputation

There are two types of amputations, congenital amputations and acquired amputations. An acquired amputation is the surgical removal of a limb, such as an arm, finger or a leg whereas a congenital amputation is a deficiency present at birth and can involve either upper limb, lower limb or both. Upper limb amputations are divided into different categories depending on the length of the residual limb, see Figure 1.

There are several conditions that can lead to the need for an acquired amputation, such as severe trauma, infection or vascular diseases [3]. In Sweden, approximately 2 550 amputations are performed each year, where about 2500 are lower limb amputations and 50 are upper limb amputations. It is predicted that the number of people living with the loss of a limb will double by the year 2050. The reason for this is an aging population and an increasing rate of people living with diabetes, which accounts for 80% of the lower limb amputations in Sweden [4]. However, the main reasons for upper limb amputation are malignancies and trauma, such as industrial accidents or war related injuries [5], [7]. One challenge with upper limb amputation surgeries is to decide on a proper amputation level and the extent of tissue to be removed. To maintain a high range of motion, it is important to keep the residual limb as long as possible, since the ability to move the limb is dependent on the length of the remaining arm. Although, to reduce healing time it is of great value to keep enough soft tissue to cover the amputation site, which can be difficult if the residual bones are kept too long [5].

A congenital amputation can be the complete loss of a limb, but more often it is only a part of the limb that is missing or deformed. The reason for the defect is in many cases not known but can be caused by genetic factors or environmental factors such as alcohol or drug abuse during pregnancy, dangerous chemicals or medication. The limbs develop during the fourth to the eighth week of pregnancy and if the woman is exposed to certain toxins during this period the limbs can be deformed. An example is the notorious case concerning thalidomide, a medication prescribed to women in the 1950's and 1960's to ease morning sickness. Later on it was found that this substance led to many children being born during these years, mostly in

Europe, with deformed limbs [8].

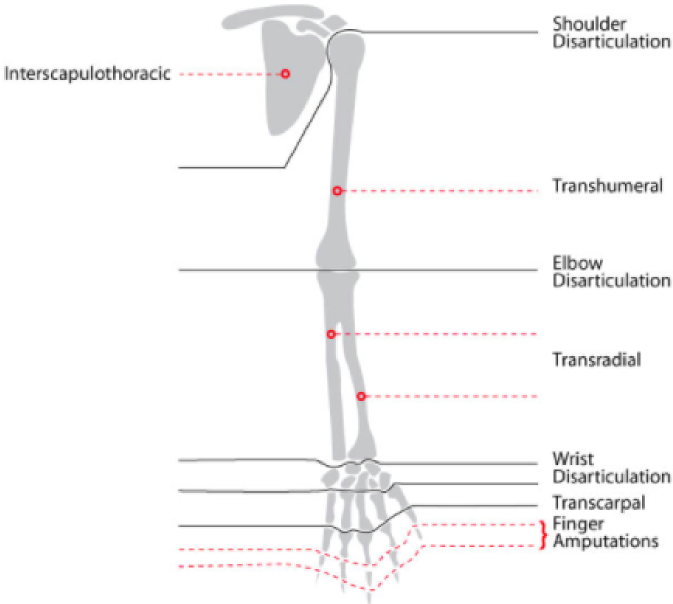

Figure 1: *Amputation levels for upper limb amputation [6].*

2.1.1 Transradial amputations

The term transradial amputation refers to an amputation of the arm below the elbow. The amputation is located somewhere along the *radius*, which is one of the two bones in the forearm, together with *ulna*. A transradial amputation leaves a functional elbow and a partly intact forearm, with a mobility depending on the individual damage. The residual limb and its distal stump can vary greatly in shape, size and sensitivity and therefore influence the possibility for the patient to use the arm in daily situations. For instance, if the transradial amputation is close to the elbow joint, the ability to rotate the lower arm is highly limited, close to non-existing. Fortunately, there is a range of prosthetic devices suitable for different levels of amputation [9], [10].

2.2 Prostheses

An amputation is a traumatic experience that will affect many aspects of the future life for the patient. A prosthesis suitable for the patient can help the rehabilitation process both mentally and physically. The ultimate aim of a prosthesis is to restore as many functions as possible from the lost extremity, with a simple and natural feeling for the user. There are three main categories of prostheses a patient can choose from today; cosmetic, body powered and myoelectric [7].

2.2.1 Cosmetic prostheses

Cosmetic prostheses are passive terminal devices used primarily for aesthetic reasons, while also providing an extension of the limb. Passive hand and arm prosthetics come in a variety of designs and materials and are often created to resemble a normal human hand, see Figure 2. For a unilateral amputee, *i.e.* a patient only amputated on one side, the prosthesis is often created with a geometry based on the sound hand. Other than providing a lifelike appearance, the passive prosthesis can for example act as a support or aid the other hand when gripping or holding objects [9].

Figure 2: *Passive fingers, hand and arm prostheses, with different designs and materials to resemble a normal human hand [11].*

2.2.2 Body powered prostheses

A body powered prosthesis uses the body of the patient to mechanically control the movements and is usually attached to a shoulder harness, see Figure 4. Cables and pulleys are integrated in both the terminal device and the harness and by altering the shoulder position the tension created will pull the cables and thus move the prosthesis [12]. The prosthetic device can be shaped as a realistic hand, though for increased functionality, body powered prostheses often have prehensors such as 'split-hooks' or 'grippers', shown in Figure 3.

Figure 3: *Left: A grip terminal device from the company TRS Prosthetics. Right: A split-hook from Ottobock [13], [14].*

The device is kept in its default position, either open or close, by an elastic spring and for movement an opposite force has to be generated in the cable [15]. Most body powered prostheses today can only produce a force in one direction, in contrast to an intact arm with two muscles in antagonistic pairs, working against each other. This means that the prehensor can only be controlled in one direction and the devices are therefore divided into voluntary opening (VO), meaning that the prosthetic hand is naturally in closed position and the user voluntarily has to open up the fingers, or voluntary closing (VC) which in contrast is open in a relaxed position. A description of a VO device can be seen in Figure 4. The preferred mode, VO or VC, is highly individual and depends on what task to perform and which system the amputee is used to. One advantage of VC prostheses is the possibility to adjust the grip-strength, whereas for a VO, the force in the grip is alone determined by the spring properties [16]. On the other hand, the VO system allows the user to relax when holding onto or carrying an object, instead of applying a constant force which is needed in the VC system.

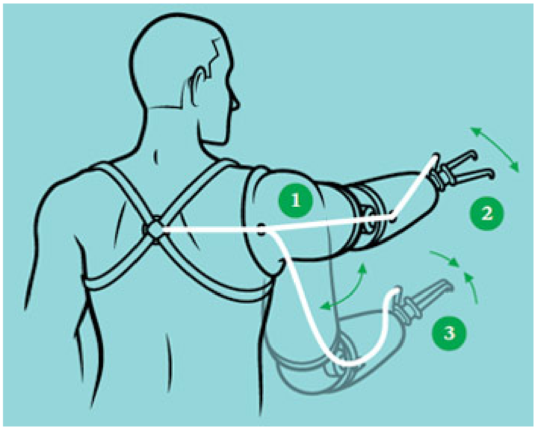

Figure 4: *A body powered prosthesis with integrated cables and pulleys for mechanical control. The prosthesis is voluntary open and is attached to a shoulder harness.* ***1.*** *By extending the arm or flexing the shoulder, a cable attached to the harness on the user's back is pulled and tightened.* ***2.*** *As the cable tightens, it opens a split hook at the end of the arm.* ***3.*** *If the shoulder is instead relaxed, the hook will be kept close [17].*

2.2.3 Myoelectric prostheses

Myoelectric prostheses are, unlike the body powered, externally powered and controlled by electrical signals produced in a muscle when contracted [14]. Electromyography (EMG) sensors register potential changes in activated muscles in the residual limb. The sensors can either be located in the socket, on the skin, above the targeted muscle, or implanted on the muscle itself. An advantage with having the sensors implanted is that the electric signals will be stronger, since they do not have to travel through tissue before registration [18]. The signals are then used as commands for the terminal device, i.e. an intentional contraction in a muscle will move the artificial hand in a specific way. Upper limb myoelectric systems range from hands with only an open or close function to very complex devices with several different hand movements. Increased precision and dexterity in a prosthesis mean that more components and parts are necessary, as well as a more powerful battery, see Figure 5. Therefore, drawbacks with myoelectric limbs include a high price and often a quite heavy device [19]. However, thanks to great advancements in electronics and signal processing the myoelectric prosthetics are continuously getting more convenient and have grown in popularity. It is also possible to combine a myoelectric prosthesis with a harness and body powered functions, for example to control more than one joint, giving the prosthesis more possible motions. For a transhumeral amputee the elbow joint can for example be controlled with motion of the shoulder and the hand with electrical signals from the muscles.

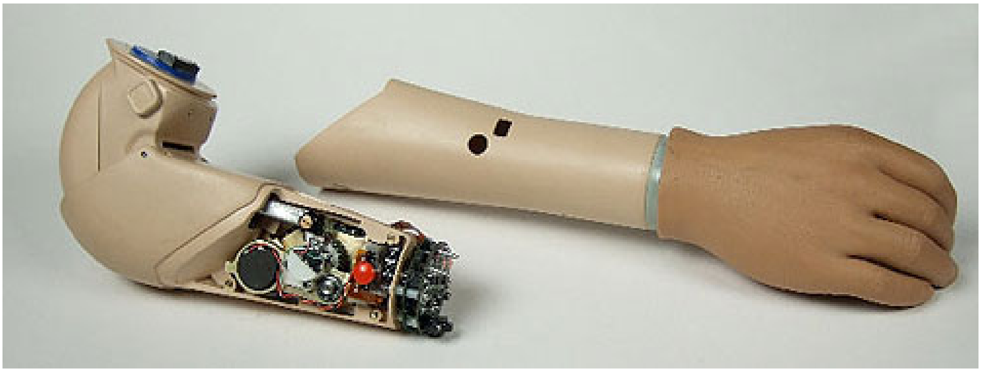

Figure 5: *The myoelectric prosthesis 'Utah Arm', from Fillauer. In this image the device is open, with the electrical system displayed inside the socket [20].*

2.3 Sockets

The socket is the part where the residual limb meets the prosthetic device. It has a significant impact on comfort, function and individual impression of the prosthesis. If the socket does not fit, or for example has sharp edges, it can result in a great deal of pain, bruises and blisters for the user and even lead to limited overall usage of the prosthesis. Every user is unique and every residual limb is different, it is therefore crucial that the socket is carefully made to fit the user perfectly [21]. The goal is to create a socket that distributes the load evenly to limit the pressure. To maintain a good alignment it is important to regularly update to socket, since the residual limb will change over time and the socket will be worn out [22].

There are different ways of creating a successful connection between the prosthesis and the arm, such as self suspension sockets, suction sockets or a shoulder harness. The self suspended sockets are designed to match the stump exactly and the prosthesis is held in place only by the socket gripping around the stump. This connection is therefore enhanced if the shape of the stump is irregular or has a bony flare. If the stump instead has a smooth surface, a suction socket can be a better choice. This solution depends on a one way valve which creates a vacuum inside the socket. However, this is only a solution if the stump is smooth and even enough, since a vacuum is hard to achieve otherwise. Both the self suspended socket and the suction socket can be combined with a shoulder harness connecting the prosthesis to the trunk. A harness can also be used independently, if the other socket solutions are not an option. The harness creates great support and is a reliable option, however, it can feel ungainly for the user [7].

The traditional way of creating a socket is using plaster. The residual limb is covered in wet plaster bandage to form a negative cast, see Figure 6. This cast is left on the patient to dry and is then carefully removed and filled with liquid plaster to create a positive cast. A test socket is made with transparent thermoplastic, formed around the positive cast with the help of vacuum, then adjusted to perfectly fit the user. Finally, an ultimate socket is created in a suitable material in the same way as the test socket [23].

Figure 6: *Plaster bandage is used to create a negative cast on the residual limb, which will after several steps result in a socket [23].*

Another possible way of creating a socket is to 3D scan the residual limb and create a digital model, see Figure 7. This digital model can then be adjusted in size and thickness before it is sent to a 3D printer. Since this is a new method and the possibilities to 3D print are limited, it is not yet widely implemented clinically, for instance not at Aktiv Ortopedtekink in Skåne. However, creating the socket this way is cost effective, could reduce working time for a prosthetist and the resulting scan is easy to adjust to better fit the user [9], [23].

Figure 7: *Digital model and 3D printed socket, created by Emelie Strömshed as a master thesis project in 2016 [23].*

2.4 Grips and hand movements

A fully functional arm and hand have many possible movements and degrees of freedom. The shoulder, elbow and wrist can all bend and rotate and the fingers can individually move in different ways. When referring to hand movements in prosthetic devices one often talks about different grip patterns, which is a combination of positions and movements in the fingers [24]. Figure 8 shows six different grip patterns. The image is taken from the protocol of the Southampton Hand Assessment Procedure (SHAP), a clinical test for analysis of hand functionality [25].

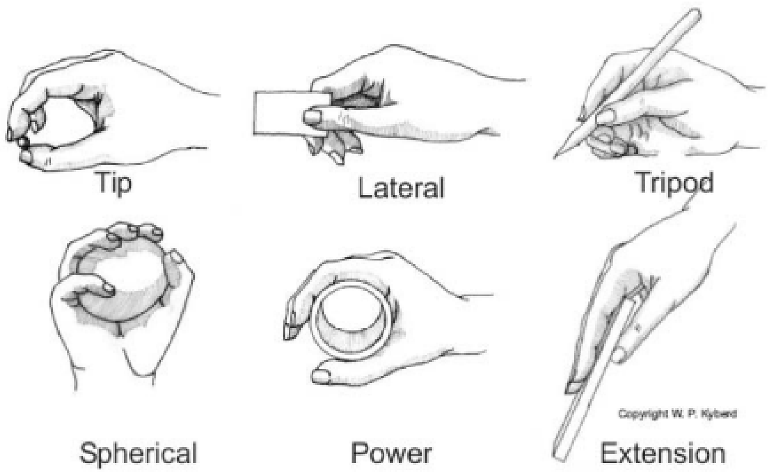

Figure 8: *Different grip patterns included in the Southampton Hand Assessment Procedure, developed at the University of Southampton in 2002 [25].*

Another important feature of the hand is the possibility to change the position of the thumb, which plays a major role in the different grasps. The thumb can either be abducted, perpendicular to the palm, or adducted, parallel to the palm, see Figure 9.

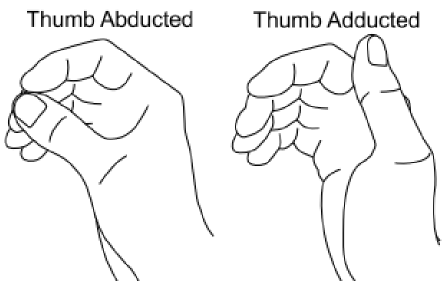

Figure 9: *Two different positions of the thumb [26].*

Many prosthetic hands used clinically today have the thumb in abducted position and one degree of freedom, open and closed, which form the "tip" or "power" grip shown in Figure 8. However, there are several new advanced prostheses, such as the Bebionic hand from Ottobock, see Figure 10. This bionic hand has 14 different grip patterns, giving the user a lot more freedom and the ability to complete more everyday tasks [27].

Figure 10: *The myoelectric Bebionic hand from Ottobock has many advanced features, such as individual motors in each finger and powerful microprocessors, resulting in 14 grip patterns [27].*

Since this is an advanced myoelectric prosthesis it requires lot of training and is suitable for users that are willing to spend a lot of time learning how to control the new prosthesis. Otherwise a prosthesis with fewer grip patterns might be a better choice, due to a shorter adjustment time. However, the main reason why the most advanced prostheses are not being used at for example Aktiv Ortopedteknik today, is the fact that this type of technology is very expensive [9].

2.5 3D printing technology

3D printing is an additive manufacturing method, see Figure 11, based on digital computer aided design (CAD) models. It was invented by Charles Hull in the early 1980's and has proven to be revolutionary both for prototyping and the product development process. Additive manufacturing is a procedure where a three-dimensional shape is created layer-by-layer from cross sections in a digital model [28].

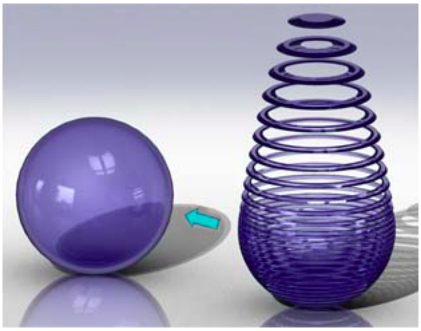

Figure 11: *Additive manufacturing method. A digital 3D model is split into thin layers, which are printed on top of each other and fused together to create the object [29].*

In the early stages of 3D printing, it was mainly used as a fast and inexpensive way to produce visual prototypes, but has since then developed into a direct manufacturing method and can produce fully functional final products. Today, 3D printing can be used for industrial mass production purposes, but the main advantage of the process is the possibility to customize the product. Thanks to this, it has had a great impact for the development of medical devices where individual needs and personalization are of great importance.

There are several different types of 3D printers, differing in the method of layer application and bonding, but the main steps of the process are the same. The primary idea is to slice the virtual three-dimensional model into very slim cross-sections and create an STL file, short for stereolithography. This 3D printer compatible file is sent to the printer for extrusion. Depending on the printing type more or less post-processing of the model is necessary, which can include the removal of support material and surface polishing [28].

2.5.1 Fused Deposition Modeling (FDM)

FDM is the most common 3D printing technique today [29]. The material used in an FDM machine is thermoplastic, which is heated up and extruded through a nozzle onto a building plane, see Figure 12. The building plane continuously moves downwards resulting in the object emerging layer by layer. To be able to create more complex structures with cavities, a support material is used and extruded, sometimes through a second nozzle. This material will be eliminated when the printing process is complete. Since thermoplastics have very good chemical and thermal qualities, this is a technique well used in a number of different industries [30].

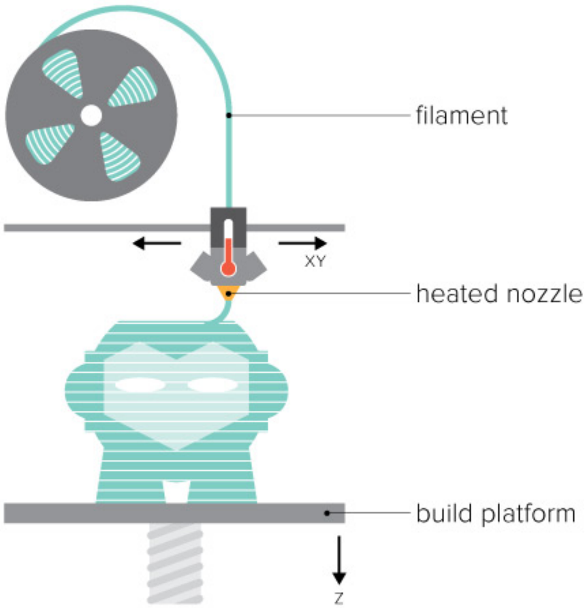

Figure 12: *A 3D printer using the common technique FDM. A thermoplastic material is extruded through a nozzle, layer by layer, onto a building plane to create the object [31].*

2.5.2 Selective Laser Sintering (SLS)

The SLS printing technique uses powdered material and laser to build up a 3D object, see Figure 13. A thin layer of the desired material, in powder form, is spread out on a building plane and the energy from a laser beam is used to melt the powder into a solid shape, a process called sintering. Like in the FDM case, the building plane continuously moves downwards and a new bed of powder is added to create the object layer by layer. When the new layer is hit by the laser beam, it is melted and fuses to the structure below. Since the powder works as a support material, there is no need for other material to hold up the structure. This means there is no need to remove material after printing, resulting in a smooth surface. [29]

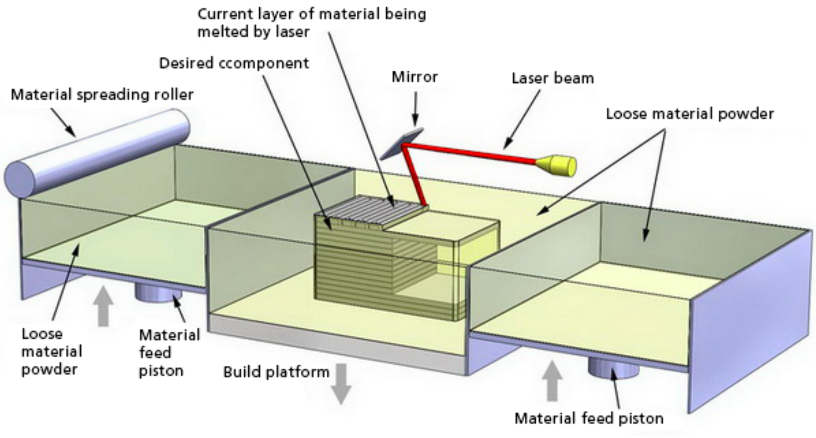

Figure 13: *SLS is a powder technique using laser to build up the object. A thin layer of the desired material is spread out on a building plane and a laser beam melts the powder into a solid shape [29].*

2.5.3 Stereolithography (SLA)

Stereolithography is a 3D printing technique where a UV-sensitive liquid resin is used as material. This liquid is hardened layer by layer with a beam of UV-laser, see Figure 14. The resin continues to cure even after the structure is printed, which means that the properties of the resin will change over time. Due to this, the SLA method is preferable when printing prototypes and not when making final products that will be used over a longer period of time. If areas of support material are needed this is created at the same time and has to be removed manually when the object is finished [32].

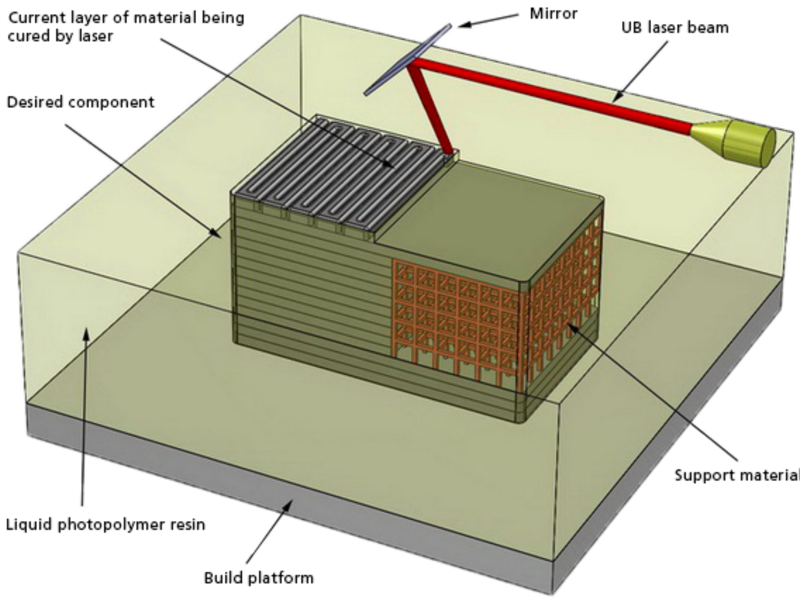

Figure 14: *SLA is a 3D printing technique where a UV-sensitive liquid resin is used as material. This liquid is hardened layer by layer with a beam of UV-laser [29].*

2.6 3D printed prosthesis

The development and accessibility of the 3D printing technology have opened up a global interest for 3D printed prostheses. With the intention to provide cheap and easily manufactured equipment for amputees in developing countries, CAD designers and enthusiasts have come together to establish foundations and organizations providing open source prosthetic devices. One example is *E-nable, A Global Network Of Passionate Volunteers Using 3D Printing To Give The World A "Helping Hand"* [33]. This network has 8000 members, with different academic backgrounds, from all over the world. All designs are open source, which allows people who have access to a 3D printer to download the designs and print their own prostheses. If that is not possible, *E-nable* can also provide the final 3D printed prosthesis at a low cost. The most common designs are for transcarpal amputees with a functional wrist, with at least 30 degrees range of motion. However, there are also some designs available for transradial amputees with only a functional elbow, for example the ones shown in Figure 15.

Figure 15: *3D printed transradial prostheses using flexion of the elbow to control the contraction of the hand. Many of the open source prostheses are intended for children and therefore have a playful design, such as the RIT Arm and Team Unlimbited Arm, both from E-nable [33].*

In general, the body powered 3D printable arms available on the web have a few design key points in common. They have a printed half-cylindrical gauntlet around the residual limb and no socket, attached and kept in place with bands made out of Velcro. Most of the open source designs are voluntary closing and in contrast to the majority of body powered prostheses used clinically, there are no shoulder harnesses used. Instead, the 3D printed devices are controlled in one of the following ways:

- If the wrist is still intact, its flexion pulls on a string and closes the fingers.
- If the amputation is transradial, the flexion of the elbow controls the string and closes the fingers.

The fingers either have two or three hinge joints each with one possible rotational direction. To keep the hand in its default position, elastic strings are run through holes in the fingers. Alternatively, as for the Flexy Hand, specific elastic hinges made from the rubber material Filaflex from Recreus are used in the fingers [34]. Therefore there is no need for elastic threads, see Figure 16.

Figure 16: *The Flexy-Hand 2, available for download at E-nable. The Flexy-Hand uses elastic hinges as joints, printed in the material FilaFlex [34].*

3 Method

This section describes the methods used throughout the thesis. Initially a project plan was written with a time frame, see Appendix C, which was used as a guidance for the rest of the work.

3.1 Literature review

Before starting the design process a thorough literature review was performed. The goal of this was to gain a better knowledge about prostheses on the market today, how far the development of 3D printed prostheses has come and how to best design the final prototype. Searches were made on for example PubMed, with key words such as *"3D printed prosthesis", "upper limb prosthetic device"* and *"body powered prosthesis"*. Websites offering 3D printed prosthesis, who share their designs, were also studied and used as inspiration, such as *E-nable, A Global Network Of Passionate Volunteers Using 3D Printing To Give The World A "Helping Hand"*.

3.2 Interviews

3.2.1 Christian Veraeus

Christian Veraeus, a prosthetist at Aktiv Ortopedteknik in Lund, was interviewed during the first week of the project. The questions asked in the interview were regarding the traditional way of creating an arm prosthesis in clinics, what goals were realistic to have for this thesis and what different kinds of methods could be used to achieve a good result. The information obtained from the interview was used to compile a number of requirements for the prosthesis, more information about these can be read in section 3.4. The contact with Veraeus was kept throughout the project with continuous meetings, interviews and guidance.

3.2.2 Patient with congenital radial amputation

A few weeks into the project an interview was held with a patient at Aktiv Ortopedteknik in Malmö. The patient was a 14 year old boy with a congenital left side radial amputation, visiting Aktiv Ortopedteknik to start the process of receiving a new prosthetic device, since his current one was outgrown. This contact was established through Christian Veraeus, the patient's prosthetist, who along with the patient and his family gave their consent for observation of the procedure and the following interviews. Different aspects of using a prosthesis were discussed during the interview, such as comfort, limitations and design. The answers from the interview were used as an inspiration in the continued work, and two more meetings were held with this patient later on in the project. The information about the thesis given to the patient before the interview can be seen in Appendix A and the questions asked in Appendix B.

The main reason why this patient did not use his prosthetic device on a daily basis was the lack of feeling in the prosthesis. Due to this he found that the prosthesis, in many situations, did not enhance his performance. Gaining a sense of feeling in an artificial limb requires sensors and electrical components and is therefore not possible when making a prosthetic device only powered by motion from the patient's body. This was therefore not followed up during this project. Anther reason for not using the prosthesis, which was easier to take into consideration, was the long time it took to change between an open and closed grip and that it was not possible to perform the lateral grip, see Figure 8. Due to the time delay when changing grip the patient felt that it was easier to use his residual limb than the prosthesis, but if changing grip could be done faster he would use the prosthesis a lot more. Additionally, the ability to change to a lateral grip would increase the function of the prosthesis in many specific situations, for example drumming, where the patient had problems with his current device. These desired functions were kept in mind when designing the prosthesis.

3.3 Design approach

After the first interview and observation, it was established that the 3D printed prosthesis should be based on this patient in terms of fit and appearance, *i.e.* the prosthesis should be customized after his residual limb and designed to match his functional right hand in order perform user tests later on. However, since this patient is only one specific user a more general approach regarding function was considered as well. Before designing digitally, drawings were made on paper to get a better understanding of size and function for the different parts, as well as how they could be combined, see Figure 17. Inspiration for the design was found in the *Flexy hand*, seen in Figure 16, and the *Team Unlimbited Arm*, seen in Figure 15, as well as other prosthetic arms found in literature.

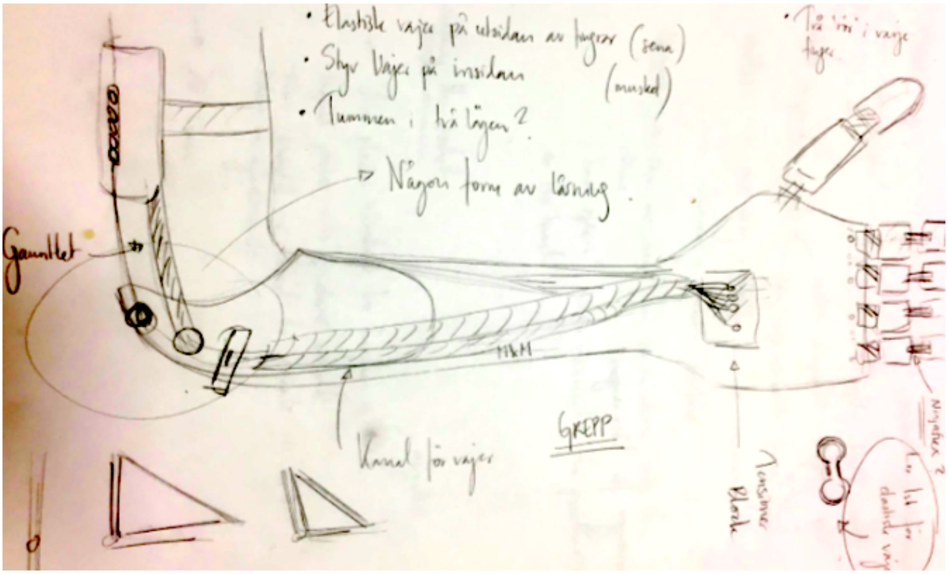

Figure 17: *The first sketch of the prosthetic arm.*

The intention of this project was also to follow up on the master thesis *"The Perfect Fit. Development process for the use of 3D technology in the manufacturing of custom-made prosthetic arm sockets"* [23], written in 2016 by Emelie Strömshed at the Department of Design Sciences at LTH. Emelie Strömshed has given her permission to use her thesis as a base for the creation of a socket in this project. The novelty with this design has been to combine Emelie Strömshed's method of 3D printed customized socket with a functional 3D printed prosthesis.

The model of the prosthesis was drawn and designed in a Computer-aided design (CAD) software, a tool with the ability to create, visualize and analyze technical 3D models. For this project, two different softwares from Autodesk^{TM} were chosen; Fusion 360 and Meshmixer [35] [36]. Fusion 360 is a cloud based CAD program with several different environments integrated, suitable for many various applications. The work in this software was mainly done in the sculpt mode, which is favorable when modeling arbitrary bodies and soft shapes. Meshmixer is a software specialized in triangle meshes, which is the mesh format generated from 3D scans, thereby useful when importing and editing 3D scans as well as preparing 3D prints. In some aspects these two softwares have similar capabilities. Although Fusion 360 has a built-in Mesh mode, a decision was made to work in Meshmixer as well, mainly because the previous thesis on 3D printing of prosthetic sockets by Emelie Strömshed was done in Meshmixer. Since the writers did not have any experience with these softwares from before, several hours were spent in the beginning of the project getting to know the interface and the different functions. This was mainly done by using the *Fusion 360 Adoption Portal* [37].

3.4 Requirements

After the interviews with the patient and Christian Veraeus, the following requirements were set up for the prosthesis:

- Comfort and stability
- Voluntary closing
- Adjustable size
- Lightweight
- Movable thumb
- Different grasp patterns
- Quick moving ability
- Friction on tip of finger to improve grip
- Locking mechanism for closed grip

Table 1: *List of requirements*

Requirement	Specification	Solution
Comfort and stability	The prostheses should have a comfortable socket to enhance stability and long-term use. No painful pressure from bands around the residual limb.	A 3D scanned and printed socket based on instructions from a previously written master thesis will be integrated into the prosthesis.
		Continued on next page

Requirement	Specification	Solution
Voluntary closing	VC function provides the ability to adjust the force in the grip.	Elastic joints in the fingers will keep the hand open when in relaxed state. Flexion of the elbow will close the hand by pulling on a wire.
Adjustable size	The 3D digital model can be scaled before printing to fit different amputees.	The entire hand will be scalable to different sizes. For simplicity, the individual parts will not be scaled one by one.
Lightweight	The prosthesis should not be heavier than an intact arm. When creating the arm prosthesis the goal is to make the mass as low as possible.	The prosthesis will be printed with a low density material and all parts except the fingers should be hollow. No electrical or extra components.
Movable thumb	The ability to have the thumb both abducted and adducted increases the amount of possible grips.	The thumb can be placed in two different positions, one on the side of the palm and one perpendicular to the palm.
Different grasp patterns	With several grip patterns the user will have the freedom to use the prosthesis in many different situations.	Thanks to the VC mechanism the force can be adjusted to keep the hand in a more or less closed state. In combination with the ability to move the thumb, different grip patterns can be achieved.
		Continued on next page

Requirement	Specification	Solution
Quick moving ability	The ability to quickly change between closed and open hand will increases the performance of the prosthesis in several situations.	The joints will be made of a flexible material that can quickly go back to its original position.
Friction on tip of finger to improve grip	To maintain a better grip and reduce the amount of force needed when grasping an object, the surface of every fingertip should have added friction.	On every fingertip an extra part, printed in a more flexible material, is added. This will increase the friction in these areas.
Locking mechanism for closed grip	The ability to lock the prosthesis in a closed position will reduce the need for keeping a constant force when holding objects.	When the fingers in the prosthesis are flexed, the wire can be locked with help from the other hand.
		Continued on next page

3.5 Printers and materials

Throughout this project, three different printing techniques have been used for prototyping; FDM, SLA and SLS, all available at Lund University. The printing techniques were tested on different components and evaluated in terms of different material properties and appearance. Factors affecting the choice of technique were also accessibility to the printer, as well as cost. The writers of the project had access and knowledge to use the FDM printer, however the SLA and SLS printed parts had to be done by the supervisor of each printing lab. The final prototype was printed with the technique that proved to be most suitable for each individual part.

In the FDM printer at the Biomedical Engineering Department at LTH, the material **FPE (Flexible Polyester) 45D** was used. FPE 45D is a compound made from a mixture of soft and rigid polymer with a Shore hardness of 45D. The Shore scale indicates the hardness, or durometer, of a material; a lower number represents a softer material and vice versa. The Shore hardness can be measured both in the Shore D or A scale, representing different standard durometer scales, where A is used for softer and more flexible rubbers and D for harder materials. See Appendix D for a reference chart of different materials and its Shore hardness. Even though the FPE 45D is a hard rubber, it is considered a soft filament in FDM printing context. Due to this, it is recommended to print at a slow speed and a slightly increased flow, along with a high bed temperature [38], [39] .

Formlabs Original is a photopolymer resin used in the SLA printer, also at the Biomedical Engineering Department at LTH. It is a specific type of modified acrylic glass, PMMA (Polymethyl methacrylate) created by Formlabs. PMMA is a strong and resistant material in terms of tension and has a density of 1,18 g/cm^3, but due to its stiffness it is brittle and does not have a high impact strength [45]. Prints in Formlabs Original are great for prototypes, giving a high resolution and a smooth surface [40].

The **Formlabs Flexible** material is another photopolymer resin used in the SLA printer. The material is very flexible when thin and more resistant when thicker. It has a Shore hardness of 80A and an elongation of approximately 80% [41].

Nylon PA12 is the material used in the SLS printer at the 3D print laboratory at Ingvar Kamprad Design Center (IKDC). Nylon is a class of several different types of polymers, where PA12 (Polyamide12) represents the number of carbons in each monomer. The material is strong and has a high thermal resistance while still being lightweight, with a density of 0.95 g/cm^3. PA12 shows elastic properties with a Shore hardness of 75D. In comparison to SLA printed materials that keeps curing by UV-light after printed, Nylon PA12 is long-term stable; making it a material suitable for durable and robust prototypes and finished products. The surface of the printed PA12 is grainy with a high friction, though it is possible to use different kinds of surface treatments for a more polished exterior [42].

Another material used in this project is a type of **Silicone** or **Polysiloxane**, a synthetic elastomer made up from chains of silicon and oxygen atoms. Silicones can be mixed with other compounds to alter the properties for different purposes. The silicone used for this prosthesis has a Shore hardness of 65A and is thus highly flexible.

The manufacturing method of the silicone parts is different from the above described materials and the components created in silicone have not been 3D printed. Instead, a template was milled out in a heat resistance type of plastic and the parts were then molded from this. The process was done at Aktiv Ortopedteknik at Lund Univeristy Hospital with the help of Christian Veraeus and David Braithwaite [43].

ThermoLyn Supra Flex was also used for creating parts to the prosthesis. This is an elastic material from Ottobock, mainly used for residual limb sockets on prosthetic devices. It is made from a copolymer of Ethylene-vinyl acetate (EVA), which is a thermoplastic and flexible material with a high toughness. ThermoLyn Supra Flex has a Shore hardness of 80A and just like the silicone, not used in 3D printing but instead molded into desired shape after heated [44].

3.6 Design Concepts

3.6.1 Finger

The primary idea when designing the fingers was to connect three different components to each other with hinge joints. Through each part there would be two holes, one for an elastic cord to keep the fingers stretched out when in relaxed state and one for the tension wire to close the hand.

This idea was later on replaced by a different concept, inspired by the Flexy Hand. Instead of elastic threads and hinge joints, the parts of the fingers would be connected to each other with a flexible joint. The joint was designed to both keep the fingers attached to each other and also to maintain the 'steady-state' position of the open hand. The shape of the joint was first planned to look like the one displayed in Figure 18, but was then altered a bit to reduce the risk of slipping out of position. Instead of having round edges the edges were made sharper. The process of designing and finding the right material for the joints can be read in Section 3.6.6.

When using the flexible joints, each part would still have a hole for a wire, which would generate the bending movement in the fingers when in tension. Also, to be able to bend, all corners and edges needed to be rounded off, see Figure 18. The angels of these slopes were calculated based on the maximal bending position and displayed in Figure 18.

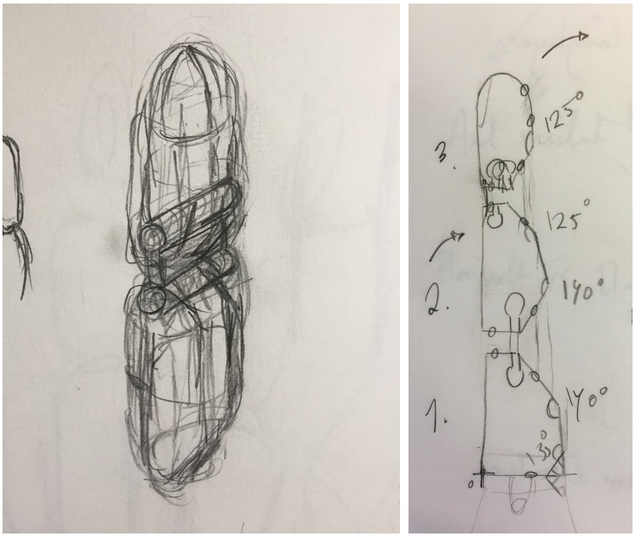

Figure 18: *Sketches of the finger which the 3D model was based on. The angels of the slopes were calculated based on the maximal bending position of the finger.*

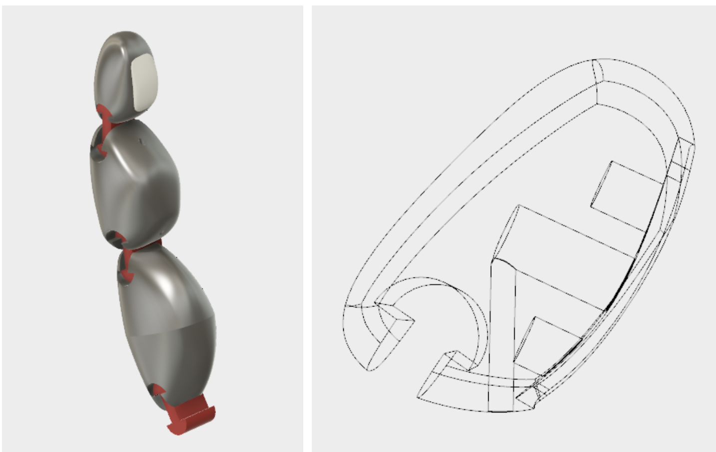

Figure 19: *Left: CAD model of the whole finger, with joints and flexible top part. Right: Wire frame of the top component of the finger, with holes for the wire and flexible part.*

The holes for the cords that run through every finger were aligned with the palmar side of each part. In the distal part of the finger the hole was wider to fit the knot of the wire, see Figure 19. Thanks to the difference in diameter between the hole and the knot, the wire would stay in place. To cover the holes, a separate part was attached to the tip of each finger. The material of this part was printed in a flexible material with a higher friction coefficient, which would act more like the human skin and enhance gripping capacity, see Section 21.

The components of the fingers were first printed in the SLA-printer using Formlabs Original, resulting in a very good shape and appearance of the fingers. However, the parts were solid and therefore very heavy. The material was also quite brittle and broke easily. The final components were therefore instead printed in the SLS printer using the material Nylon PA12. The same model was used for every finger though scaled downed for the little finger.

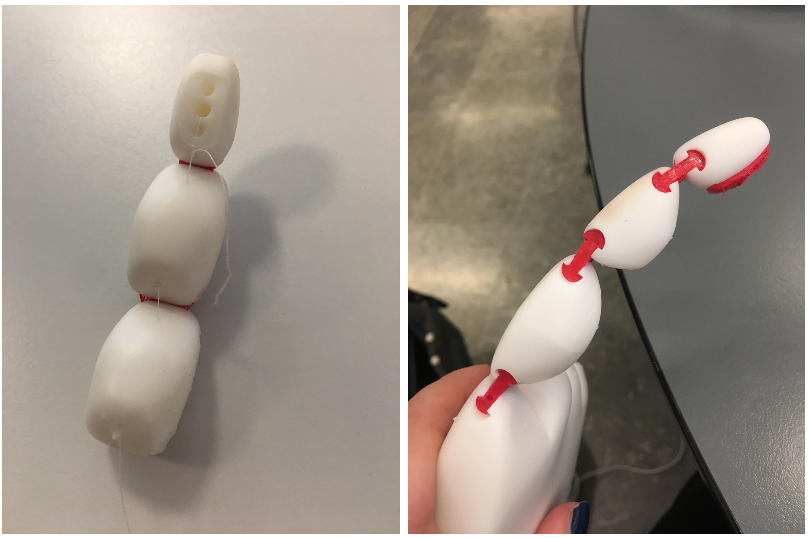

Figure 20: *The first prototype of the whole finger seen from the front and from the side.*

3.6.2 Fingertip

To increase gripping capacity the idea was to use a different material for the fingertips. This material would have a higher friction and therefore enable a better contact surface when gripping an object. This extra fingertip would also cover up the holes were the wires would be inserted, to give the finger a nicer appearance, see Figure 21. The fingertip was designed separately in Fusion 360 and aligned with the surface of the top component of the finger.

The first version of the fingertip was printed in the Ultimaker 2 FDM printer using Flexible FPE 45D. The material gave an improved grip, however the parts had an uneven surface due to a lot of support material and therefore the result was not perfect.

The final fingertip was printed in the SLA printer using the material Formlabs Flexible. This material did also have a good gripping capacity but there was still a problem with too much support material. This support material could however be cut away quite easily after printing and was therefore considered to be the best result.

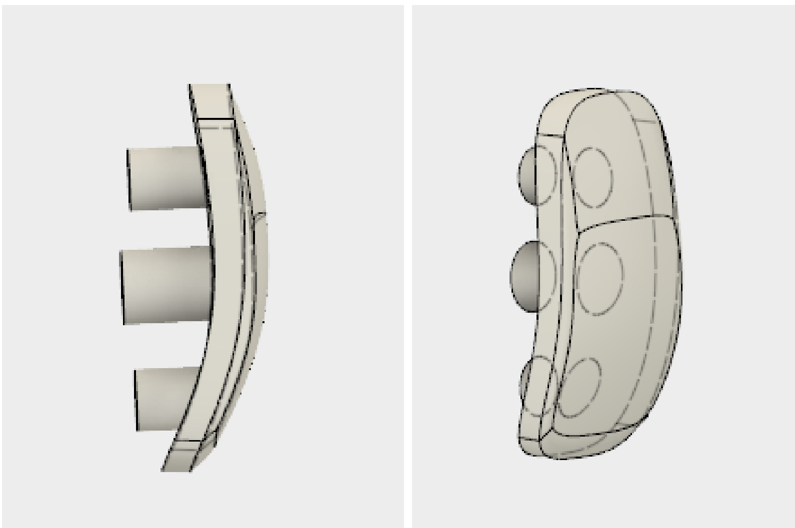

Figure 21: *The model of the final fingertip.*

3.6.3 Thumb

To enable more than one grip, the thumb had to be movable, which was achieved by connecting the base of the thumb to the palm with a pivot joint, see Figure 22. Holes in the palm, both above and under the pivot joint, together with two small rods would keep the joint in place. The length of the rods was shorter than the holes so that they could be inserted before the joint. The joint could then be slided into position and the rod would fall into place. To avoid the rods falling out of place two small springs were placed between the rod and the palm.

To prevent accidentally changing the position of the thumb, a locking mechanism was implemented. The lock was placed in the top rod of the pivot joint mechanism. A handle was added to the rod and the holes were extended so the handle could be reached from the lateral side of the palm. When the rod is in the upper position the thumb can be moved and when the rod is in the lower position the thumb is fixed, since the rod would then combine the palm and the thumb. The rod could only be set into two lower positions and thanks to this, the the thumb would be fixed in both an adducted and an abducted position, see Figure 22.

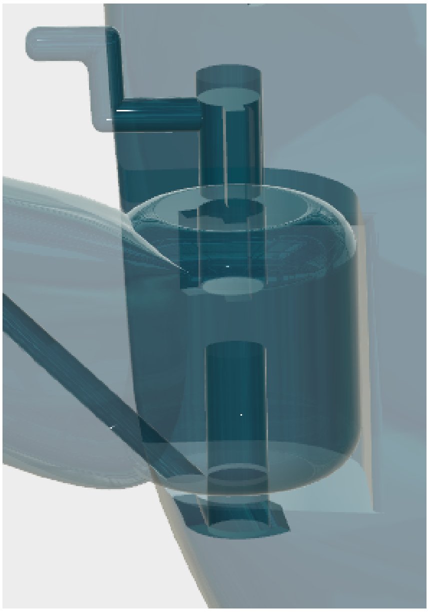

Figure 22: *The pivot joint connecting the thumb to the palm, with the locking mechanism in unlocked position.*

When designing the thumb the two upper components from the other fingers were used, but upscaled. The first idea was to skip the joint between them, since it was believed that the joint would not increase the range of motion. Instead, the parts were combined and fixed in a set angle, see Figure 23. In this case the hole for the wire did not start at the fingertip but on the lower part. Since the wires from the thumb and the rest of the fingers had to move at the same time and with the same amount of force this design of the thumb limited the overall movement of the fingers. Due to this, the second model of the thumb was designed with two joints just like the other fingers, see Figure 24, and the wire then started from the fingertip to enable movement in all joints.

Figure 23: *The first prototype of the thumb with only one flexible joint. The CAD model to the left and the printed model to the right.*

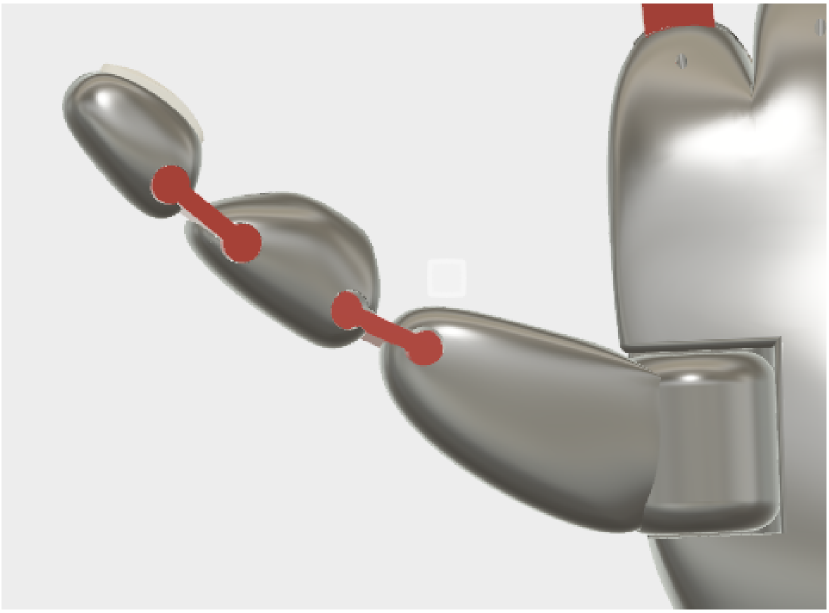

Figure 24: *Second model of the thumb with two flexible joints.*

Just like the rest of the fingers, the tip of the thumb was printed in a flexible material with higher fiction to enhance gripping capacity.

3.6.4 Hand and arm

The arm and hand were designed to look as natural as possible, with soft edges and knuckles where each finger would be attached. To reduce the weight, the hand and arm were made hollow. The first prototype of only the hand was printed in Formlabs Original with the SLA printer, shown in Figure 25.

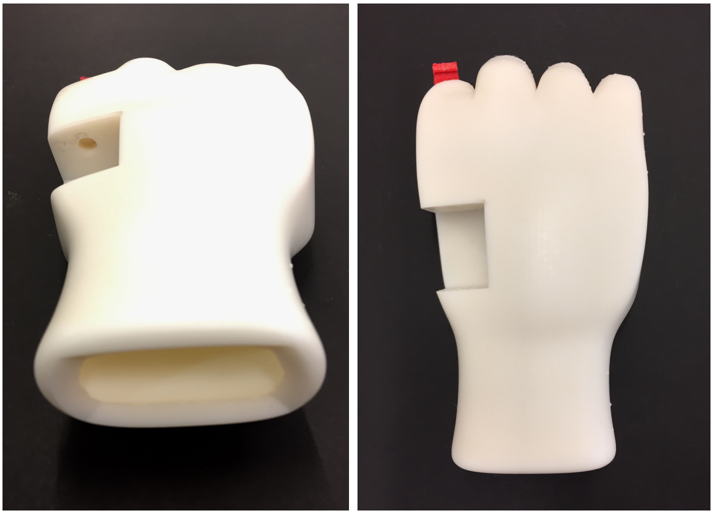

Figure 25: *The first version of the hand printed in Formlabs Original acrylic glass.*

The print gave good results regarding shape and appearance; the material had a nice and polished surface, however, it was very brittle. This is a typical property of SLA printed materials, which is why it suits well for a prototype though not as a durable finished product. Additionally, the following points were considered defects on the first model and improved for the second prototype:

- Size; the palm was a lot bigger than the patients hand and was scaled down for a better match.
- Weight; the walls of the model were reduced from 5 to 2 mm.
- The holes for the joints were placed too close to the edge, making the remaining wall too thin.
- Choice of material and printing technique; the Formlabs Original was too brittle.

In the second model, all the above mentioned defects were fixed and improved. The arm was also extended, in order to create a wrist as well as a section for attachment to the socket. Due to the elongation and curved geometry of the arm, a track for the wires was created. This would lead the wires from each finger to the back of the socket, where it could easily be lead through and attached to the gauntlet, see Figure 26.

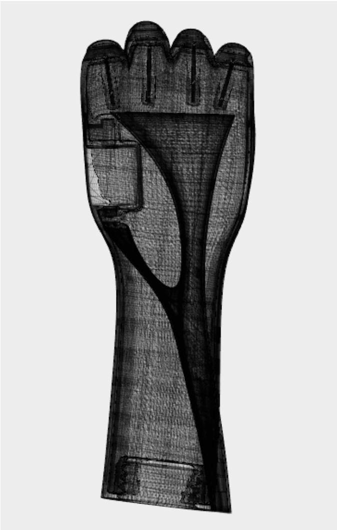

Figure 26: *Arm created in Fusion 360, showing the paths were the wires are led through the hand to the socket.*

3.6.5 Socket

During the interview with the patient at Aktiv Ortopedteknik, a socket was made by the prosthetist Christian Veraeus, using the traditional method with plaster bandage. This socket was then scanned and imported as a mesh into Meshmixer to model and create a printable socket. The steps in the *Booklet User Guide* created by Emelie Strömshed were followed, including smoothing of the mesh and trimming the surface, to reduce pressure on sore or protruding areas of the limb [23]. This modified mesh, now defining the inside of the socket, was thickened to 2 mm and the outer surface was further smoothed for a nice appearance. The 3D model of the socket, shown in Figure 27, was then imported to Fusion 360 to allow integration with the arm and hand. Furthermore, connectors to the gauntlet were added, see Figure 28.

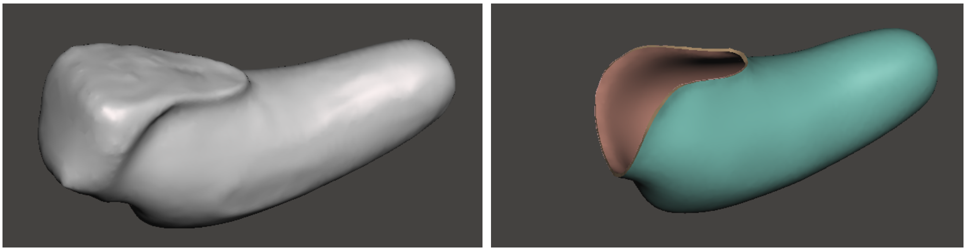

Figure 27: *3D scan of patients limb and the modeled socket in Meshmixer.*

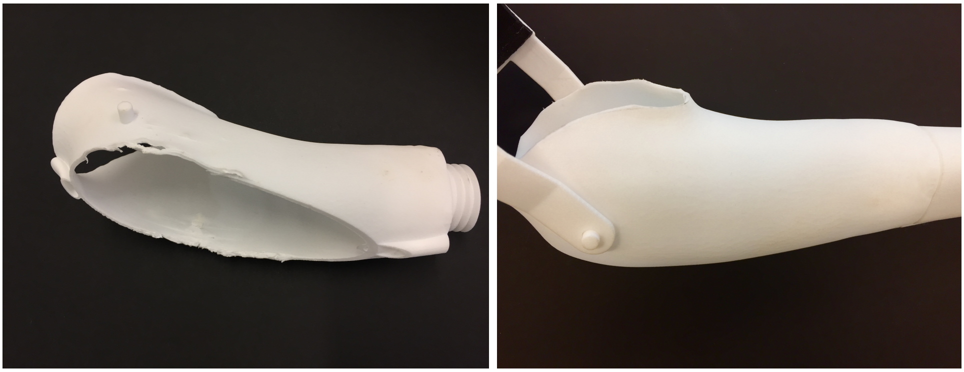

Figure 28: *Two sets of the printed prototypes of the socket. Left: The first print failed due to problems in the printer. Right: The final prototype.*

3.6.6 Elastic joints

The elastic joints have the main function of returning the fingers to its original position after a contraction. They also connect the finger components to each other. The alternative to using a flexible material in the joints was to use an elastic wire, but to reduce the number of holes in the palm and extra parts in the prostheses the option with elastic joints was chosen. With the intension to make the construction more stable and reduce the risk of the elastic joints slipping out of position, the ends of the joint ware designed as half circles with sharp edges, see Figure 29.

The first version of the elastic joint was printed in the flexible material Flexible FPE 45D using the Ultimaker 2 FDM printer. In the first attempt the layers did not fuse together properly, probably due to low temperature in the nozzle. Even though the settings were changed and the temperature was increased, the second attempt was not any better, see Figure 29. The filaments were falling apart and the joint could not be used properly in the finger.

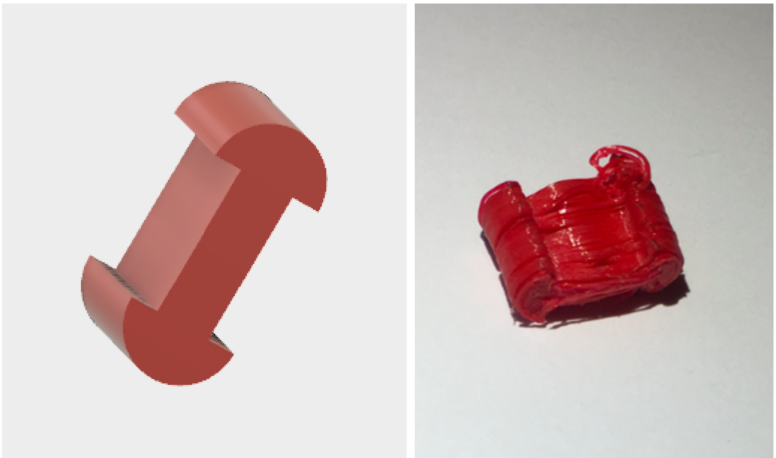

Figure 29: *The design of the first version of the elastic joint from Fusion 360 and the second failed attempt of the FDM printed model.*

The second version of the joint was printed with a flexible resin in the SLA printer. The joint bent easily but it took a long time for the joint to get back to its original position, which was not desirable since the user would not have the required quick motion of the hand. The material, Formlabs Flexible, had an elongation of approximately 80% [41], which in this case was too low and the material did not withstand the stretching forces that occurred on the outer side of the joint leading to a fracture on the side, see Figure 30.

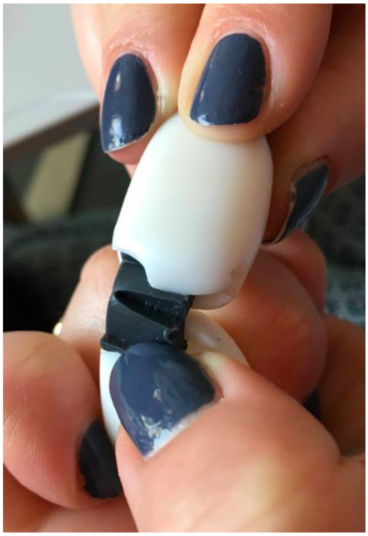

Figure 30: *The second version of the elastic joint was printed in a flexible material in the SLA printer. After bending the joint several times it broke.*

Since the previous tested materials, both FPE 45D and Formlabs Flexible, did not possess enough strength a new concept was chosen. A template of six joints was milled out from a plastic block and the joints were moulded in two different materials; silicone and Thermolyn Supra Flexible. These joints were the strongest so far and did not break from continuous bending. They also quickly returned to their original position which was a requirement for the joints. However, the Thermolyn Supra Flexible gave more stability to the finger in the relaxed position and was therefore chosen as the best material for the joints.

To reduce the pressure on the edges at the long sides of the joints, changes were made on the last version and the half circle was replaces by a complete circle, see Figure 31. The length of the joint was also increased to create a bigger surface in between the finger parts to simplify the bending.

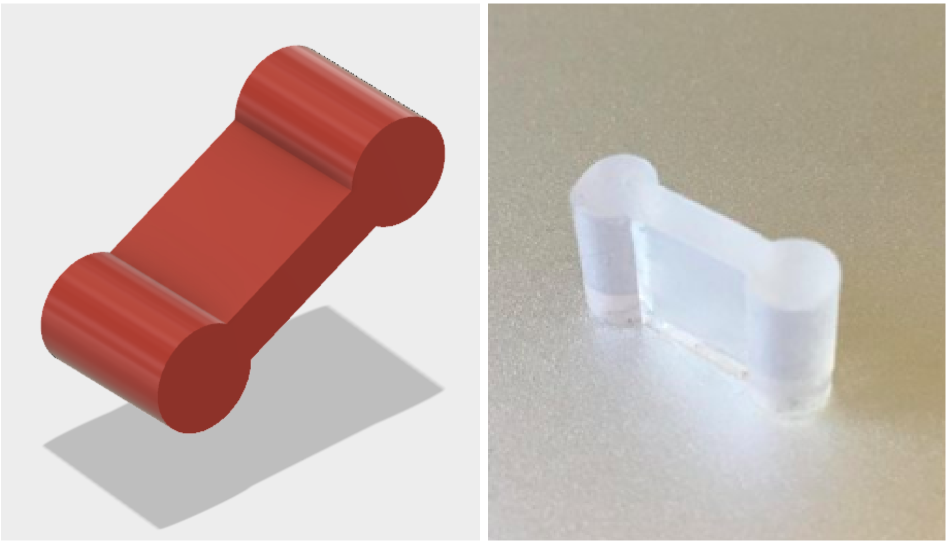

Figure 31: *The final model of the elastic joint with round edges and the moulded joint in Thermolyn Supra Flexible.*

3.6.7 Gauntlet

To enable contraction of the fingers when moving the elbow, the wires had to be fixed to a separate part above the bending point. To achieve this a gauntlet was designed and connected to the socket, see Figure 32. The gauntlet moves together with the elbow and creates a tightening of the wires which will move the fingers towards each other.

On the back of the gauntlet, two compartments were placed, the first to direct the wires and keep them in the middle, and the second to keep the wires attached. Screw holes were made on the top one to simplify the assembling of the prosthesis, see Figure 32. Each wire would be tied to one screw and thanks to this the tightening of each wire could be individually adjusted, allowing for a more precise adjustment of the tension in each finger.

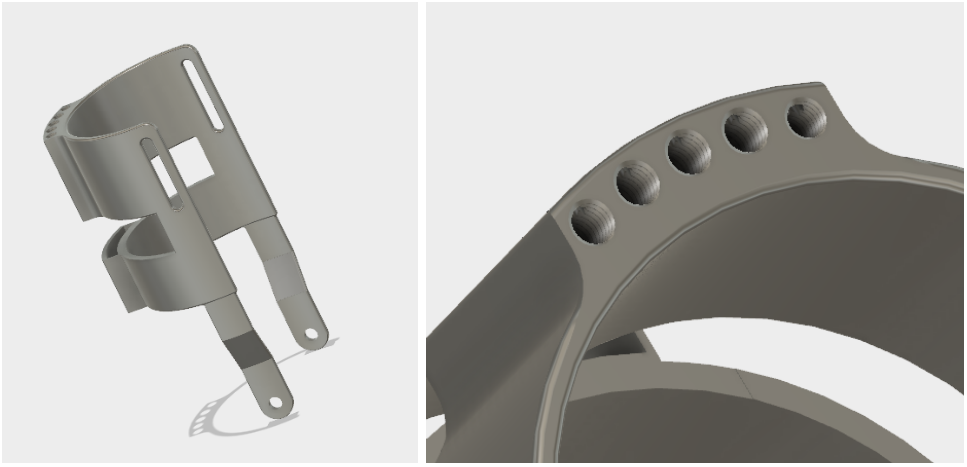

Figure 32: *The model of the gauntlet in Fusion 360.*

3.6.8 Assembling the CAD model

All components of the prosthesis were created as separate files in Fusion 360, as described above, but put together in one file to get the full picture of the limb. Digital joints were used to position the parts in relation to each other and to perform simulations of movements. Additionally, some parts had to be completely fused in the CAD model; the socket, the hand and the pathway for the wires. Due to different advantages of the softwares when working with meshes, both Meshmixer and the mesh mode in Fusion 360 were used when combining the components.

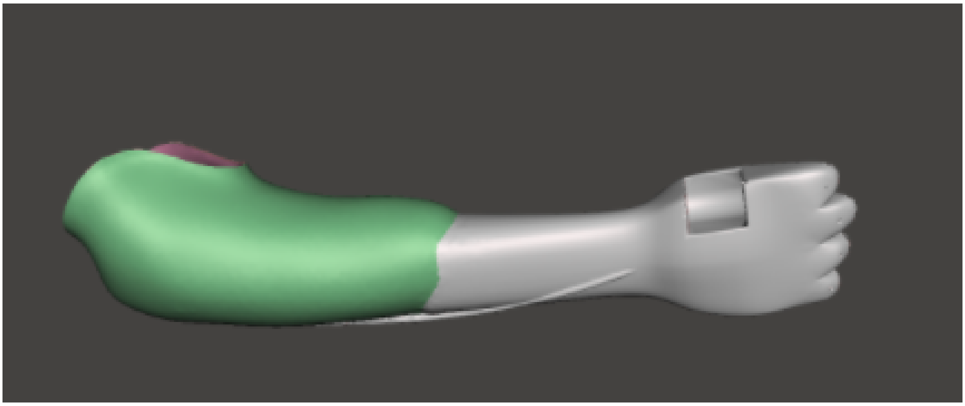

Figure 33: *Arm created in Fusion 360, fused together with the socket in Meshmixer.*

As previously mentioned, the original idea was to print the socket and arm in one piece, but due to the change of printer from SLA to SLS, it was no longer possible to print a part that big. Instead, the body of the fused arm and socket were split into two, see Figure 34. On one side, a threaded hole was created and on the other a threaded cylinder to enable simple assembling after printing. Finally, the components were saved as individual STL files and sent for printing.

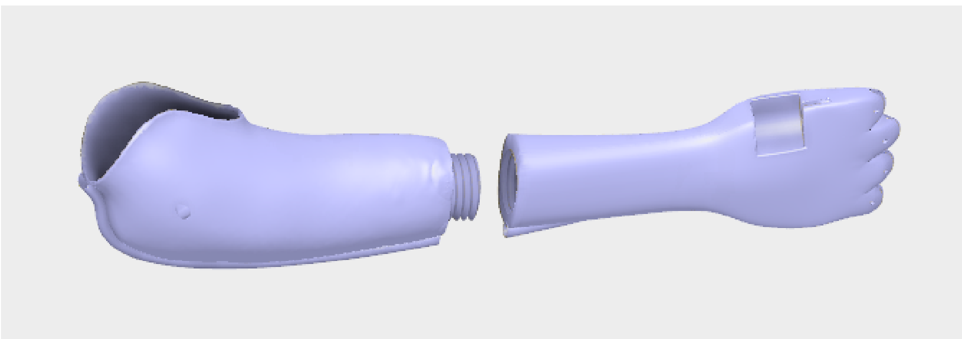

Figure 34: *The prosthetic arm split in two parts to fit in the SLS printer.*

3.6.9 Printing and assembling the prototype

The final prototype was printed in the SLS printer at the 3D lab at IKDC and the material used was Nylon PA12. The two parts of the arm were screwed together and the different parts of the fingers could then be connected with the wire. To create better comfort in the gauntlet parts of foam rubber were cut out and placed on the inside were the arm is in contact with the material. A Velcro band was placed through the holes of the gauntlet to make it stay in place and foam rubber was glued to the inside of the Velcro to improve comfort.

3.7 Testing of the prototype

During the second meeting with the patient, the first prototype of the hand, seen in Figure 25, was brought to visually compare to his other hand. It was obvious that the prototype was too big and the model had to be scaled down .

After the final prototype was printed and assembled the prosthesis was tested by both the writers and the patient. Before meeting the patient, the bending motion of the elbow was simulated to ensure that everything was connected correctly and that the fingers could move. When this was established a user test was performed at the patients house in Karlskrona. The results from this user test is described in Section 4.4.

4 Result

This section describes the final prototype and how well the result reflects the goals and requirements that were set up in the beginning of the thesis.

4.1 Components

The following table summarizes the different components of the prosthesis. It shows the choice of material used for each part as well as the result.

Table 2: *List of the different components in the final prototype.*

Component	Printer/Material	Result
Elastic joints	Moulded/Thermolyn Supra Flexible	Good flexibility and strong, though not stable.
Finger components	SLS/Nylon PA12	Nice shape.
Palm and arm	SLS/Nylon PA12	Slightly too small.
Finger tips	SLA/Formlabs Flexible	Good friction and form.
Gauntlet	SLS/Nylon PA12, Velcro and foam rubber	Comfortable and good form.
Socket	SLS/Nylon PA12	Too small, too much friction but good shape.
Thumb	SLS/Nylon PA12	Nice shape.
Wires	Fishing line	Hard to tie, good size.

4.2 Final prototype

For the larger parts of the prototype, the SLS printer was chosen for the final print, since the Nylon PA12 was not as brittle as the acrylic glass, Formlabs Original, used in the SLA printer. However, the finish of the surface with the SLS printer was not as smooth and polished as with the SLA printed one. The small holes in the fingers and hand had to be opened up with a drill due to left over material being stuck inside the holes. The result of the entire prosthesis is shown in Figure 35 and 36. Unfortunately, there was a problem with the mold for the joints, which is why the little finger is missing in the images. Due to limited access to the SLA printer, no fingertips could be printed to match the second edition of the hand. Instead another flexible rubber material was cut in the right shape and glued to the fingers.

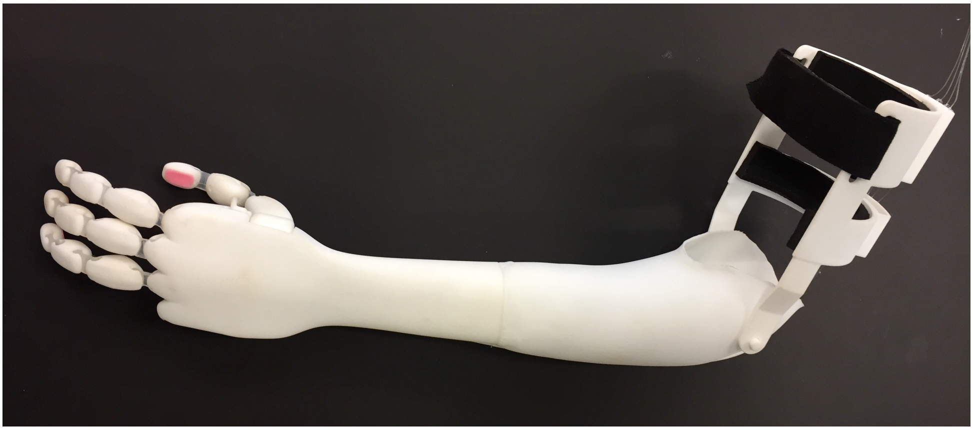

Figure 35: *The final prototype displayed from the dorsal side. The little finger is missing in this version.*

Figure 36: *The final prototype displayed from the palmar side. The little finger is missing in this version.*

Testing the range of motion in the gauntlet resulted in functional movements of the fingers. The index finger and the thumb could meet to create the tip grip and the hand could grasp different items by closing all fingers around it, see Figure 37.

However, there was a lack of strength in the contraction and the hand could not clench hard enough to hold onto heavy objects or irregular shapes. Additionally, after repeated contractions the fingers did not move as easily as in the beginning. This could be due to the fact that the holes in the fingers and arm were quite small and the wires got caught due to friction and rough patches. To assure that the function is kept during a longer time period, larger room for the wires is needed.

Figure 37: *Testing the grip of the final prototype.*

The gauntlet was printed in Nylon PA12 and in the holes a Velcro strap was put to create a more comfortable fit and also enable flexibility regarding size, see Figure 38. The holes for the screws were not circular due to printing failure and the screws could not be inserted.

Figure 38: *The printed gauntlet connected to the socket and the Velcro straps. The wires are tied to the gauntlet due to problems with inserting the screws.*

4.3 Requirements

How well the result reflects the requirements have been rated according to the following scale. Further discussion regarding these scores can bee read in Section 5.2.

- 1 = No attempt to solve this was performed
- 2 = Attempts to solve this was performed but not with a good result
- 3 = Acceptable result
- 4 = Good result
- 5 = Excellent result

Table 3: *The result of the requirements*

Requirement	Result
Comfort and stability	4
Voluntary closing	5
Adjustable size	3
Lightweight	5
Movable thumb	3
Different grasp patterns	3
Quick moving ability	4

Friction on tip of finger to improve grip	4
Locking mechanism for closed grip	2

4.4 User test

In the end of the project, the final prototype was tested on the patient to get feedback both on comfort and function. The socket created from a 3D scan from Aktiv Ortopedteknik had been adjusted and made bigger than the original scan, since 3D printed material has a higher stiffness than the material used in the clinic. Despite this, the socket was too small to fit properly on the residual limb. In clinics, a lubricant is often used to facilitate the insertion of the residual limb into the socket. However, this was not helpful in this case due to the rough inner surface of the prosthetic socket. As a result, the function of the prosthesis could not be tested in a completely realistic way, though the test still gave a good sense of how the prosthesis would function for the patient. The size of the hand and arm was good and resembled the right arm of the patient. The wrist however could be thicker to be in better proportion to the rest of the prosthesis.

Despite the fact that the socket was too small, the comfort of the prototype was good. The gauntlet fitted properly and was of suitable size and length. The patient did not feel that the gauntlet was uncomfortable in any way. In comparison to the patient's original prosthesis, the prototype was apprehended as lightweight and could be worn with low effort.

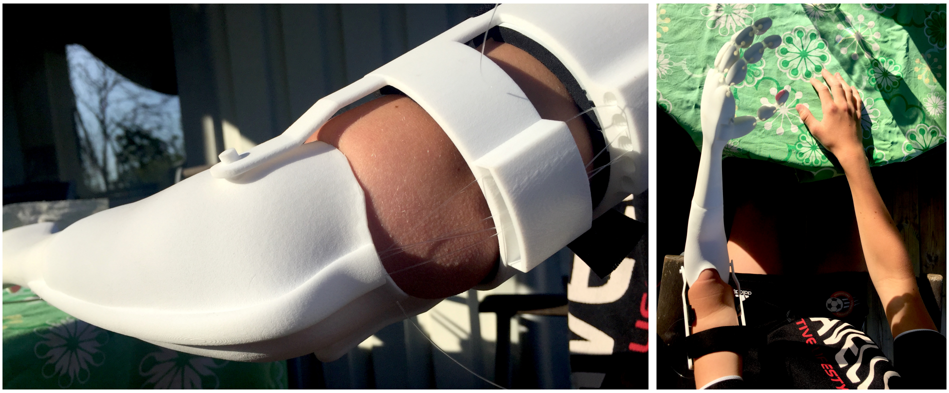

Figure 39: *The final prosthesis tested by the patient. It shows the gauntlet being too small to fit the residual limb.*

The user test further indicated that to obtain a good gripping function, it is important that the thumb and index finger have a wider contact area than in the present model. It was also obvious that the way of moving the thumb has to be more simple. It was too hard for the patient to change the position of the thumb because of friction between the surfaces in the locking mechanism.

Figure 40: *The final prosthesis tested by the patient showing the good size and resemblance to the right arm.*

The user test also showed that the untreated Nylon PA12 is not the ideal material for this purpose, duo to the high friction. If the material had been smoother, like the Formlabs Original, it would have been easier for the patient to insert the residual limb into the socket and also to move the thumb. When the nylon is in contact with another surface of nylon, as in the thumb lock, the friction is too high, which makes it almost impossible to move.

5 Discussion

This section discusses the method used during the project as well as the final result. Limitations and error sources are presented along with further improvements that could be done if more time would be added to the project.

5.1 Method

From the start of this project, the planning and structuring of the process were considered important aspects. A lot of time were given in the beginning of the thesis to create a strategic and clear time plan, along with a continuously kept journal throughout the project. Organizing the work like this has been very helpful and given a good overview of the progress and drawbacks of the method. Though the steps of the plan were followed, there are always parts of a project that take longer than planned as well as unexpected steps or problems. The CAD developing and designing process was one of these. Since the writers did not have much preceding experience with Fusion 360 or Meshmixer, a lot of time in the beginning of the project was spent on learning these new softwares. In hindsight, this learning period was probably not as long as needed. This resulted in unnecessary steps later on in the design process, when parts of the prosthesis had to be thoroughly redesigned or completely remade from the beginning due to small defects. With a greater knowledge of the software before starting, changing of the design could have been done faster and thus saved time.

5.2 Result

The components of the final prototype were made with different printing methods and different materials, both to obtain the optimal properties for each part but also due to constrained accessibility of the printers. As a result, the manufacturing of the prototype has several separate steps, leading to a longer time to create the whole prosthesis than if the same method and material had been used. The optimal method would have been if all components were made with the same printer, however it was chosen to prioritize the function above saved time. Another factor that could be considered is the cost of the prosthesis and the effect that the several manufacturing methods have on this. Since the final step of the project is a functional prototype and not a finished product, no consideration have been taken to the price reduction that could probably be done if only one type of printer was used. This is however an important aspect in any eventual future work.

Further discussing points in the project are more specific procedures in the design concept. One of these is the size of the holes where the wires pass through. Due to the small holes in the components, extra time was needed to open up the holes with a drill. To improve the prosthesis these holes should be enlarged in the digital model to save time and resources after the print. Another feature which would be changed if an additional prototype was printed is the pathway for the wires, see Figure 26. Since the hand and arm was ultimately split in two parts, the canal is only really necessary on one of the sections; the socket. The existing solution has tubes inside the hand, which now do not serve any purpose. Instead, the hand should be completely hollow with only a passage to the pathway on the socket to eliminate the use of redundant spare material.

In Section 4.3 each requirement was graded from 1 to 5 using the following scale:

- 1 = No attempt to solve this was performed
- 2 = Attempts to solve this was performed but not with a good result
- 3 = Acceptable result
- 4 = Good result
- 5 = Excellent result

The following paragraphs explain why these results were obtained and what could be improved to advance these numbers.

- **Comfort and stability - 4**
  Since the socket is created from a 3D scan of the patient's residual limb, it is possible to create a perfect fit, making the socket both comfortable and stable. However, since the untreated surface of the nylon has high friction it was hard for the patient to put the socket on. To improve this the socket either has to be upscaled, or the surface has to be made more smooth, for example by

coating the Nylon PA12. The result from the user test showed that there were no specific pressure points but since it did not fit completely this cannot be known for sure. If more time was available the size of the socket would be the first thing to improve, in order to thoroughly evaluate the function with proper user tests.

- **Voluntary closing - 5**
  The decision to make the device VC was mainly based on the fact that many similar 3D printed hand prostheses are designed that way, along with the impression that it felt most natural when discussing with Christian Veraeus. As previously mentioned, the open source printed hands are primarily designed for people with a functional wrist. Therefore, the critical point of the design in this project was the flexion angle of the elbow could give a long enough extension of the wires to bend the fingers. The final prototype showed a good result when testing the hand without the patient. Unfortunately, since the socket was too small the closing of the hand could not be tested when the prosthesis was worn by the patient.

- **Adjustable size - 3**
  The final prototype was designed and customized for the patient but the size can be adjusted to fit others. If a 3D scan is performed on the residual limb of another patient, the size of the rest of the prosthesis can be adjusted after this. However, this was not a main focus during the project and therefore more time would have to be devoted to create a more simple way to adjust the size.

- **Lightweight - 5**
  One requirement when designing the prosthesis was to make the mass as low as possible. In contrast to a prosthetic leg, where you need some weight to create a natural feeling, a prosthetic arm does not. Instead, a heavy prosthesis will feel more in the way and can be a reason for not using it at all. To achieve this requirement, all parts in the resulting prototype were hollow. The density of the nylon used for all components is around 1 g/cm^3, resulting in the prototype weighing 520g. It was confirmed from the patient during the user test that that he experied the prototype as significantly lighter than the myoelectric prosthesis he is using today.

- **Movable thumb - 3**

To implement the idea of a movable thumb, the thumb was designed differently from the other fingers. The concept of the locking mechanism consists of a small part inside the hand that slides down to make the thumb stay in two specific locations. The solution worked fine when simulating it in the CAD software but when printed in Nylon PA12 the locking mechanism had some issues. As a result of the grainy and rough surface, the sliding of the lock did not work. To improve this, the margins between the small part connecting the thumb and the hand should be expanded and printed in a smoother material. Even though the thumb could not be moved between the two positions, they were well placed and looked natural.

- **Different grasp patterns - 3**
  Besides the movable thumb which would allow the hand to complete several grips, different grasp patterns were planned to be obtained by adjusting the tension in the wires of the separate fingers. Due to a small deformation of the gauntlet when printed, the holes on the top did not end up circular, but oval. Consequently, the screws could not go into the holes. Still, some level of adjustment was possible, by individually tying the wires on top of the gauntlet. If there would have been time for another round of printing, the different grips could have been better evaluated and fine tuned.

- **Quick moving ability - 4**
  When evaluating the speed and agility of the 3D printed hand, the patient's original myoelectric prosthesis was used as a reference. To close and open the electric hand, the patient has to contract two individual muscles on his forearm. The reacting movement of the fingers has a delay and is quite slow. In contrast, the mechanical contraction of the 3D printed prototype is immediate when the strings are pulled. As for the opening of the fingers, the elastic joints were responsible for this movement. As explained in Section 3.6.6, several different joints were tested and resulted in different speeds to open the hand. The final joints were stiffest and therefore returned to its relaxed position fastest, leading to a good result for this requirement.

- **Friction on tip of finger to improve grip - 4**
  The small components on the tip of each fingers serve two purposes; primarily enhancing the friction but also covering the holes where the wires enter the finger. The fingertips were printed in the SLA printer in Formlabs Flexible

material along with the first prototype of the hand and fingers and gave a great result in terms of size and grip. However, due to limited access to the SLA printer, no fingertips could be printed to match the second edition of the hand. Instead another flexible rubber material was cut in the right shape and glued to the fingers. This solution does not fully represent the idea with the printed parts, but still shows a great improvement in grip ability of the prosthesis.

- **Locking mechanism for closed grip - 2**
  The requirement for a locking mechanism would allow the arm to stay closed even when the elbow is not flexed. Finding a solution turned out to be harder than planned and due to the time limit no idea was implemented into the CAD model during the project. It was however initially considered an important concept in the function of the prosthesis, the ability to lock the hand in a certain position would give the user a lot more freedom. A locking mechanism would therefore be a priority if the project would continue for a longer period of time.

5.3 Limitations and error sources

The most significant restriction in this project has been the limited access to the printers and also a limited amount of materials. Consequently, this means that the material used might not always have been the best alternative. With more time, more materials could have been requested and purchased by the lab for evaluation. Another source of error has been that the printer used for the final prototype is printing many models at the same time. Due to this, the components from this project have been dependent on other models both in terms of their design during printing and of collecting enough files to make it worth running the machine. If the printer contains one model that fails due to poor design, it will affect the other models as well. The socket had to be printed three times due to printing failure of other models in the same batch, see Figure 28, which has of course led to a delay in the final result.

Another limitation has been the cost of printing. The price is calculated depending on the entire volume the model takes up in the printer and not the actual material usage. Since the prosthesis is quite large and has an uneven shape, printing at the lab was expensive. Therefore the prototype could not be printed as many times as wanted. If the project budget would not have been an issue, parts could have been printed more often and then adjusted after every print to improve the result.

5.4 Ethical aspects

There are plenty of research regarding prostheses today and the prosthetic devices are more advanced than ever. However, with increased functionality comes a higher price, meaning that the devices are becoming more inaccessible. This is an issue worldwide; who decides what kind of prosthesis a patient can have? In many places the patients alone have to pay for their devices, contributing to an unequal distribution of leading edge prosthetic equipment. Additionally, there are amputees without the opportunity to get a prosthesis at all, which could be due to either poverty or lack of educated prosthetists and knowledge. In Sweden prostheses and rehabilitation equipment are provided by the county council, though not with the possibility to fund the most advanced devices for everyone. What a patient want might not always be the best or viable alternative and therefore it is the prosthetist's job to determine the choice of prosthesis for the patient. This once again gives rise to an important question: How much should be you own decision and what is up to the experts?

5.5 Future work

The main goal of the project has been to create a simple, yet functional transradial prosthesis. This has been achieved, however, there are several things that can be improved. The design process took longer than expected and therefore less time was focused on evaluating the result. The final prototype was only tested once on one patient. To make the result more reliable the prototype needs to be tested several times and the design adjusted in between these tests. To verify that the prosthesis is functional it should also be evaluated on a group of patients. This was not possible during the time frame of this project, since the socket would have had to be customized for every patient, but it is definitely a future possibility.

If more time would have been devoted to the project, more focus would be on making the prosthesis stronger and able to grasp heavier object. Since the joints can bend in both directions, the strength of the fingers is only dependent on the force exerted from the wire. Therefore, the hand is not as stable as desired in its relaxed position and also not strong enough to hold onto heavy objects. One way to improve this could be to connect the finger components in the back which would counteract bending backwards.

Since a VC prosthesis was chosen, the idea in the beginning of the project was to design a locking mechanism for making the prosthesis more useful for the patient. Without this function, the patient needs to hold the contraction constant when gripping an object. With a functioning locking mechanism the prosthesis could be locked in the closed grip, which would be of great value for the user and therefore significant in future work.

6 Conclusion

The aim of this project was to create a body powered 3D printed prosthetic arm and evaluate the 3D printing technology for this purpose. The objectives have been achieved and resulting in a prototype only controlled by flexing the elbow. An existing method for custom made sockets based on 3D scanning has been used, which means that the final prototype combines the comfort of a personalized socket with a 3D printed hand and arm. The final prototype is lightweight, easily maneuvered by the user and with a simplistic design. However, many aspects still require future work to develop a fully functional prosthetic device.

The project has further showed that 3D printing is an incredible method with potential to make prosthesis more customized, cheaper and produced faster. Hopefully this area will continue to grow and spread to help more patients. Much research is done but mainly through organizations, the next step would be to implement this method in the health care sector and use the 3D scanning and printing technique in clinics.

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Appendices

A Information about the thesis given to the patient

LUNDS UNIVERSITET
Lunds Tekniska Högskola

2018-02-13

Information om projektet

Projekt: Design och 3D-printing av kroppsstyrd handprotes.
Studenter: Malin Klerstad och Matilda Svensson
Handledare LTH: Christian Antfolk
Handledare Aktiv Ortopedteknik: Christian Veraeus

Vi är två studenter från civilingenjörs programmet Medicinsk och teknik på LTH. Vi läser nu sista terminen och skriver vår master-uppsats inom biomekanik och rehabiliteringsteknik. Målet med vårt projekt är att designa och 3D-printa en enkel men väl fungerande kroppsstyrd armprotes.

Ditt deltagande skulle hjälpa oss att förstå vilka parametrar som är viktiga för användaren av protesen. Vi kommer använda dina svar för att försöka skapa en så bra protes som möjligt. Ditt deltagande innebär en intervju och sedan lite längre fram i vår testning och utvärdering av vår prototyp.

Vid intervjun kommer skriftliga anteckningar tas men dina svar kommer inte kunna kopplas till som person.

Ditt deltagande är helt och hållet frivilligt och du kan välja att avsluta din medverkan utan att uppge orsak.

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B Interview February 19th, Aktiv Ortopedteknik Malmö

- Har du haft protes tidigare? Vilken typ?
- Hur lång tid tog det att lära sig använda protesen?
- Är den bekväm?
- Vad skulle kunna vara skönare?
- Vid vilka tillfällen använder du/använder du inte protesen?
- Vad kan du göra/vad kan du inte göra?
- Vilket grepp är viktigast?
- Kan du sträcka ut handen?
- Är det viktigt för dig att kunna sträcka ut fingrarna ordentligt?
- Kan du hålla i en penna?
- Hur mycket feedback får du från stumpen?
- Kan du "känna" din hand?
- Hur mycket stöd får du från protesen?
- Kan du ta emot dig med protesen om du ramlar?
- Skulle du tycka att det var värdefullt med en flyttbar tumme?
- Vad skulle du vilja att din protes skulle kunna göra?
- Hur skulle du vilja att din protes såg ut?

C Time schedule

	Jan		Feb				March					April				May				
	Project week																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Discover																				
Planning	■																			
Pre-study	■	■	■																	
Define																				
Requirments			■																	
Design				■	■															
Develop																				
CAD				■	■	■	■	■	■	■	■	■	■	■	■					
Printing											■	■	■	■	■					
Deliver																				
Evaluation																■	■	■		
Presentation																			■	■
Report writing			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		

D Shore hardness

Reference; Shore hardness scale taken from Seals Unlimited [46].