3D Printed Prostheses and Organs

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Abstract:

Additive manufacturing allows to transform a two dimensional image into a three dimensional object by printing layers of material successively. Because of this, it has a wide number of applications in the fashion, automobile and medical industries, just to cite a few. In the latter, 3D printed prostheses have been created to help those missing a limb, allowing them to get prosthetic arms and legs for a cheaper price than normal ones and that work just as fine, if not better. In addition to that, scientists in the field have focused on one of the most pressing problems humans face nowadays, partly because of an ageing population – organ shortage. There are an increasing number of elders whose organs fail and therefore, need transplants. Some problems of transplants are their high price, how hard it is to find a suitable donor and that there is always the danger of the receiving side’s immune system rejecting it, even if the operation is performed successfully. The ultimate goal would be to be able to create organs with a 3D printer, possibly using some sort of biological ink, which can create blood vessels once implanted on a patient. However, this raises a question – can this be used to increase humans’ life expectancy? And if so, is that ethical? To answer these questions a survey is performed in order to discover just how moral 3D printed prostheses and organs are and whether society is ready for them or not. Also, a prosthetic arm is designed and analysed using SolidWorks to give an insight into the process.

Keywords:	Additive Manufacturing, 3D Printed Prosthesis, 3D Printed Organs, Survey, SolidWorks
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1. Introduction

1.1 Background

With 3D-printing it is possible to transform a two dimensional image into a three dimensional printed model (that can have almost any desired shape) by printing layers of material successively. The more layers there are, the better the resolution of the material is.

Due to this it has applications in military, archaeological and medical fields, just to mention a few. In the latter, prostheses to substitute missing parts of the human body have been created. In addition to that, it has already been used to create surgical models so as to plan operations and guide the construction of implants for patients. With this in mind, it is not hard to imagine that scientists have focused on one of the problems that have bothered humans for ages – organ failure.

The fact that society is now facing an ageing population cannot be denied. There are more and more elder people whose organs may start failing and therefore, need a transplant. Even though medicine has advanced a lot in the last decades, transplants are expensive, it is hard to find a suitable donor and even if the transplant is performed there is always the danger of the patient’s immune system rejecting it. The ultimate goal, due to all of this, would be the use of stem cells to create some kind of biological ink.

This makes people question just how ethical 3D-printed organs are. And questions also arise when contemplating the use of 3Dprinted prostheses, even if it is not such an invasive process – are they useful? Do they support as much weight as human parts? What are the differences?

1.2 Objectives

- Design a 3D-printed prosthesis of a human arm using SolidWorks
- Test the prosthesis.
- Analysing how ethical 3D-printed organs and prosthesis are.

1.3 Relevance of the problem

Research of this kind is undoubtedly very relevant nowadays. 3D printers have been in existence for a while but it has not been until recently that society has started to experiment with them: producing food, musical instruments, cars and drones between other things. And now, also prosthetics and organs.

If this could be done successfully it would help with the organs’ shortage the world faces nowadays, with any problems regarding rejection of transplants by the immune system and it would lower the price of prostheses as demand would likely not grow but there would be a much greater supply. What there might possibly be a greater demand of is jobs – helping also to lower the unemployment rates.

Therefore, this topic is relevant to humanity as a whole; parents whose kid is missing a limb would not have to go change their prosthesis (and pay a lot of money) every time the child grew a couple of centimetres – they could just slightly increase the measurements of the prosthesis in the design file and 3D print it at home. People experiencing organ failure would not have to wait months or even years to get a new kidney, new intestines, a new liver. Life could be made easier for so many people, even going as far as to avoid someone's death.

1.4 Relationship to existing knowledge

This thesis is focused on explaining step by step the procedure of creating a prosthetic arm with SolidWorks, a programme studied in Arcada mainly during the first and second year of Material's Processing Technology's Bachelor degree. It wants to prove 3D printed prostheses are the improved version of regular ones, modelling something from scratch but obviously inspired by other people's designs as there has been plenty of creations of prosthetics using this method or a similar one both for animals and humans, which is how it is known that they work and give exceedingly good results.

It goes one step further with the analysis of why is it commonly said in the media that 3D printed organs and prostheses are unethical and if they really are considered that way, which is what might differentiate this piece of writing from others.

2. Literature review

2.1 Additive manufacturing

Additive manufacturing, commonly referred to as 3D printing, is a process in which dimensional objects can be created parting from a design done in a computer. There are many different types of 3D printers, and, therefore, these objects can be created in plenty of different ways.

2.1.1 History of 3D printing

While additive manufacturing has been around for a long time – since the 1980s, although at that time it was known as Rapid Prototyping[1] – it has only been recently that the price has decreased enough for people to be able to acquire printers for personal use.

Back in 1980, a Japanese doctor called Hideo Kodama of Nagoya Municipal Industrial Research Institute was the first person to create a single beam laser curing approach. He applied for a patent, however, missed the one year deadline and failed to file all the requirements on time.

Afterwards, a French team whose members were Jean-Claude André, Alain le Méhauté and Olivier de Wiite filled a patent for stereolithography that was granted in January 1986.[2] Alain le Méhauté, back then, was carrying out some research on fractal geometry and wanted to create an object whose local properties were equal to its global properties but no machine available at that time could do that. With the help of Olivier de Wiite (who told him that when two lasers cross each other a liquid could become a solid) and Jean-Claude André (who proposed the idea of building the object layer by layer), they started looking into the possibility of building a 3D printer.

Sadly, the project had to be abandoned due to the fact that those in leadership roles were unable to see the potential of something as innovative as this.[3]

The first patent of 3D printing as we know it today can be traced to 1986. An American inventor named Chuck Hull was the first person to create the SLA machine, or 3D printer, which was special because it allowed the creation of 3D models with data files. It was the first ever device that was able to print a real object from a computer generated file. He went on to fund 3D Systems, a company that even nowadays engineers, manufactures and sells 3D printers.

Even though these are the events that left the biggest mark in the world, that does not mean that there was no other background activity going on such as the creation of Ballistic Particle Manufacturing by William Masters, the invention of Laminated Object Manufacturing by Michael Feygin and the patent of three-dimensional printing by Emanuel Sachs et al, between others.[1]

3D printing started, then, becoming popular. But, as previously stated, not in the same way smart phones have become popular nowadays – not in the public sense. Its popularity was more within enterprises from different industries as it was a fast and accurate way of creating prototypes of products.

It was not until the mid-2000s that the first additive manufacturing machines were commercially viable.[1] Also, around this time, the possibility of printing with various materials became real which offered a wider variety of options for those who wanted to produce something. All this, as well as the creation of MakerBot in January 2009, made 3D printing accessible for the general public and nowadays there are websites such as Thingiverse[4] in which people can share their own designs, communicate with one another, help each other and educate themselves on the growing topic that is 3D printing.

2.2 Types of 3D printers

Many 3D printing methods have been developed throughout the years and some of the most acclaimed ones will be briefly described below. Some of them are not used anymore today while others are on the peak of their popularity.

Others, such as **Stereolithography**, are still being used nowadays even though they are an old way of 3D printing. For creating an object with this method, a printer called stereolithograph apparatus, that converts liquid plastic into a solid, is required.[5] This one, as well as most techniques, requires a computer file containing information about the design specifics to process the object which must be in a format that the printer can understand.

The difference between stereolithography and other printers is that the former does not work by extruding a certain quantity of ink, they use "*excess of liquid plastic that after some time hardens and forms into solid object*"[5], which is why parts built this way usually have smoother surfaces.

Digital Light Processing, or DLP for short, is a comparable process to stereolithography and was created back in 1987 by Larry Hornbeck. This technique requires a source of light and a liquid crystal display panel as well as micro mirrors laid out on a semiconductor chip.[5] The material used is a plastic resin in liquid form whose behaviour varies due to light, becoming solid in just a few seconds.

Fused Deposition Model (FDM) was developed by Scott Crump in the 1980s. It is a method that can print objects with thermoplastic materials which is why those objects have surprisingly good chemical, mechanical and thermal properties – it also leads to FDM being able to produce final functional and long-lasting products and not just prototypes. Companies such as BMW and Nestle use this procedure on their products.[6]

In **Selective Laser Sintering** (SLS), that is a technology developed during the 1980s, a laser is used as the power source to fuse particles together.[6] A wide variety of materials can be used to print with this methods, always powdered substances. SLS printers are most expensive because, as previously stated, they require the use of lasers, which explains why this method of 3D printing is not usually used by the general public.

Very similar to SLS is **Selective Laser Melting** (SLM) which was created in 1995[6] and also uses a laser to fuse and melt metal powders together. Parts that have complicated geometries or thin walls are likely to be produced with this method. However, it is also not widely spread amongst the general public but mostly medical and aerospace manufacturers use it.[5]

It was in 1997 when **Electron Beam Melting** (EBM) was created by a Swedish enterprise called Arcam AB. The procedure is very similar to that of SLM with the difference that, as its name clearly states, it uses electrons as the main source of power instead of a laser. It is used to 3D print metal parts[6] and, as is the case with SLM, is able to achieve complex geometries. The parts produced with this method are considerably strong and dense.

Last but not least there is **Laminated Object Manufacturing** (LOM) was established by a Californian company named Helisys Inc.[5] It is a quick method for the creation of prototypes and, in it, laminated layers of plastic or paper are fused together by heat and pressure.[6] While it is one of the most rapid 3D printing technologies, it is also not the most well-known. It is affordable due to the cheap (when compared to others) materials used.

2.2.1 Printing procedure

Generally speaking, when it comes to their procedure 3D printers can be divided in two different groups: those that use layer after layer of material to create objects and those that bind raw materials together in order to make them.[7]

The former are the most familiar printers, as they are those present in offices, universities and homes. As stated, they deposit material into layers until the object is finalized. Their technical name is "fused deposition modelling" or, for short, FDM.[7] The latter typically have a laser (or electrons as is the case of EBM) acting upon the material using either heat or light to fuse it into the desired object.

The FDM's process starts with a design file saved in a format compatible with the printer. This is because the printer's software has to convert the file into something it can read and work with. Once everything is read, then the path the print head has to follow while extruding the material (usually 3D printed plastic created especially for this purpose – ABS, PLA, PVA…[8]) and the actions it has to performed are calculated. Then the printing can actually start.

Anyone who has seen a 3D printer of this kind operate knows that it moves vertically and horizontally and that the first thing done is outlining the shape of the object to be printed and then filling it. The process is repeated, usually for hours.

The second group of printers can, itself, also be divided into two groups: stereolithography and laser sintering.[7]

Stereolithography also requires a design file in a specific format in order for the machine to read it. Therefore, the process is quite similar to FDM until the selection of the material. What is used in this process is an especially sensitive liquid polymer that solidifies by coming in contact with UV light[9] and is treated by a laser beam that follows the outline of the desired object.

The moving platform where the material is located is lowered a certain small amount after each layer (making the material sink into a tank filled with a photopolymer), revealing a new surface and repeating the whole process again and again until it is over. The platform can be then moved again, upwards this time, to reveal the results.

It is not uncommon to clean the obtained object after the procedure is done, to get rid of the excess of resin. In addition to that, it must be put inside an oven with UV light, to harden further.[9]

Although stereolithography has many advantages such as the high resolution of the produced object, it has also drawbacks – the fumes emitted can be toxic for human beings and it is a relatively expensive method.[8]

With a very similar procedure to stereolithography, laser sintering uses powders rather than liquid photopolymers.[7]

The printing process goes as follows: the laser beam “sketches” the powder material, which melts wherever the laser comes in contact with it. The platform where the powder is deposited is then lowered and a roller inside of the printer creates an unaltered layer of powder above the previous one.

One of the reasons for printing with powder instead of liquids is the fact that whatever it is being printed unlikely to collapse due to the powder acting as built-in support. Additionally, more materials can be obtained in powder form.[8] However, the surface of the final product is not as smooth as with other methods.

2.3 Applications

At first, people were somewhat sceptical about additive manufacturing, wondering about the potential of such a thing. Nowadays, this technology has been used to create parts of cars and smartphones, fashionable clothes and shoes, equipment needed in the medical industry and even artificial organs.

When 3D printing was known as “rapid prototyping”, that is mainly what it was used for – creating a physical first version of a product in order for it to be tested. Nowadays, that is still one of its applications seeing that big companies such as Microsoft try their latest video games controllers by first producing a prototype version that will be 3D printed.[10]

Meanwhile, in the automotive industry companies such as General Motors and Ford use additive manufacturing to test parts of their cars.[11] In the case of Ford, prototypes of the vehicles' brake rotors, cylinder heads, knobs and vents were created by 3D printing. Similarly to this, the Urbee 2 (Figure 1), a car that will be made mostly of 3D printed parts is being created by a team of engineers led by Jim Kor.[12] It is called Urbee 2 due to the fact that there was a first car named Urbee who only had a 3D printed body.

Figure 1: Urbee 2, a car mostly made of 3D printed parts. (Kor Ecologic, 2013)

In the aerospace industry, enterprises such as NASA are planning to send astronauts to space with 3D printers so that they can print whatever they need.[11] The fact that this is a technology that does not use moulds, that does not require assembly and that produces no waste makes it possible so that astronauts no longer have to take spare parts with them.[13]

Fashion designers are also gathering inspiration from additive manufacturing technology, so much in fact that a 3D printed dress debuted in the New York Fashion Week. It was a collaboration between the trio of artists threeASFOUR, the designer Travis Fitch and the printer manufacturer Stratasys.[14] The dress is visually very complex (Figure 2) and extremely colourful – not something the general public would wear on a day to day basis. However, this will lay the foundation for this particular application of 3D printed objects to gain importance.

Figure 2: Dress designed by threeASFOUR in collaboration with Stratasys that debuted in New York Fashion Week. (Ponyboy magazine, 2016)

Another interesting application for this technology is found in the food industry. While is something that so far is only a concept, maybe in the next twenty years we will see 3D food printers in each house. Theoretically it could be done – extruding liquid plastic through a print head is not that difference from extruding chocolate or cake frosting[7], but practically it is more difficult, as probably people would react poorly to being served printed food.

Of course that it could be done does not mean it is an easy process. The mechanical force needs to be the correct one and the raw ingredients need to have a specific consistency for it to work.[7] And when these two conditions are not a problem anymore, an important question arises "how fresh will the food be?" because printing cookies is not the same as printing vegetable slices. Furthermore, 3D printers as we know them today do not yet have the technology to cook whatever it is they are printing.[7]

2.3.1 Medical industry

Today, the medical applications of 3D printers are not as numerous as one would think. According to members in the department of Ophthalmology in Pennsylvania[15] additive manufacturing is a 700 million dollar industry and out of those, only 11 million dollars are invested in the medical industry. Nevertheless, in the next 10 years it is expected that 3D printing grows to be an 8.9 billion dollar industry and that over 20% of that is spent on medical implementations.

Thanks to additive manufacturing doctors could give patients a more customizable care without having to worry about the number of medical devices in stock[16] as it would be relatively easy and quick to just 3D print new ones whenever needed.

3D printed hearing aids are also a reality (Figure 3). As are Invisalign custom made braces (Figure 4), which have been very successful with those people doing customer-facing work that did not want to wear normal braces. Actually, dental implants in general have become huge accomplishments for the implementation of the additive manufacturing industry.[7] Spinal and hip implants have also been fabricated.[16]

Figure 3: 3D-printed hearing aid. (Forbes, 2013)

Figure 4: 3D-printed Invisalign custom braces. (Digital Trends, 2016)

It would also be helpful when teaching medicine students how to perform a certain surgery. By showing them three dimensional examples of what they need to do the danger of something unexpected happening is reduced and the whole operation will take less time. And, in the meantime, it could provide easy to understand interpretations of the most complex parts of human's anatomy.[17] Besides, the use of dead bodies for training could easily be discarded by making 3D printed models of a patient's body.[16]

The process for the creation of these products is very similar – first, the part of the body in question needs to be scanned. The data obtained from the scan is sent to a laboratory where they convert it into a file that can be 3D printed. The materials used are usually ceramic, rubber or clear plastic.[7]

3D printed prosthesis

Something that had a big impact in Spanish medical society was when a nine-year-old child from Galicia, called Unai, was given a bionic arm prosthesis (Figure 5) fabricated with a 3D printer by four vocational training students with the help of their teacher.[18] Unai himself chose the colours for his prosthesis – green and orange, which is yet another example of how customizable objects done by additive manufacturing are, giving people who otherwise might have been ashamed of their lack of limbs the possibility to live a normal life.

Figure 5: Unai with his bionic arm prosthesis. (La Voz de Galicia, 2016)

The fact that this child could have a bionic arm for free was thanks to the initiative Enabling The Future. It is a network created almost by accident whose members use their 3D printers to create completely free prosthesis (mainly hands and arms) for those who need them. By collaborating with one another the volunteers were able to create completely functional designs that they share with each other as well as with the entire world.[19]

And this is not the only case like this. Emma Lavelle is a girl whose legs were up to her ears and her shoulders were internally rotated due to an illness called *arthrogryposis multiplex congenita.*[11] Her parents heard about a conference in which Dr Tariq Rahman was presenting WREX (Wilmington Robotic Exoskeleton) which was completely 3D printed by him in collaboration with a team of engineers. Emma was given one of those exoskeletons and could lift her arms up to her mouth for the first time in her life.[11]

Approximately 30 million people in the world are in need of prosthetic limbs but less than 20% have them (especially in under-developed countries)[20] due to the amount of work that is involved to create one and to the shortage of prosthetists.

This is only a reason why 3D printing is used. It is, after all, revolutionary method that has had an impact on so many other industries that it does not seem strange it will also change the medical industry as we know it today.

Other reasons why printing prosthesis with additive manufacturing is starting to become so important nowadays is the fact that a kid missing their fingers or, in the case of Emma Lavelle, needing an exoskeleton, would easily outgrow their current prosthesis in half a decade at maximum. With this method, the original design can be easily re-scaled and re-printed whenever needed.[20] 3D printed versions are much cheaper, too, costing around 45 euros when a "normal" powered prosthesis could easily cost thousands.[20]

And, in this case at least, cheaper does not equal worse. Jose Delgado Jr, a man who was born without parts of his left hand, had been trying prosthesis after prosthesis trying to find one that worked for him. One of the latest prosthesis he had tried was a 42,000 dollars one that controls the motion of the fingers by muscle signals from the forearm.[21] However, when he compared it to one that was given to him by a volunteer of Enabling The Future he found the latter was better for driving and carrying bags. It also permitted mobility in all fingers while the expensive prosthesis he had before did not.[21]

Jeremy Simon, the volunteer that gave Jose Delgado Jr the prosthesis, explains in a YouTube video how it works: "*...a series of non-flexible cords running along the underside of each finger, connecting to a "tensioning block" on the top rear of the device (the "gauntlet"). The tension is caused by bending the wrist downward. With the wrist in its natural resting position, the fingers are extended, with a natural inward curve. When the wrist is bent 20-30 degrees downward, the non-flexible cords are pulled, causing the fingers and thumb to bend inwards. A second series of flexible cords run along the tops of the fingers, causing the fingers to return automatically when tension is released.*"[21-22]

3D printed organs

Regardless of all the advantages additive manufacturing technology seems to have, expectations for it are exaggerated, not only by the media, but also by those who work with it such as researches or engineers.[23]

This leads to uncertainty and people wondering when something will actually be put in practice, as is the case with organ printing. It is undeniable that it is an exciting new possibility and that some progress is being made towards achieving it, however, it is not expected to happen anytime soon.

Printing organs with 3D printers would solve one of the biggest problems nowadays – the shortage of available organs for transplants. In the United Kingdom, for example, the waiting time for a kidney transplant is of approximately 944 days.[24] This is because the demand is bigger than the supply, as life expectancy has increased considerably in the last fifty years and the world is now facing an ageing population with a great number of elderly people whose organs fail and need to be substituted.

To how expensive transplants can be and how difficult it is to get a suitable organ donor adds the danger of the immune system rejecting the transplanted tissue, which is also a big concern.[25] This is the reason why the ultimate goal when it comes to 3D printed organs is also the creation of some kind of biological ink that prevents the body from attacking the newly transplanted organ.

When there is a “foreign” object entering somebody’s body, the immune system may reject it and that is a fact known by most people. This is due to the fact that germs, poisons and other kind of harmful substances have a certain type of proteins on their surface called antigens and a person’s immune system is able to recognize if they belong to that same body or not because they are different and therefore they do not match.[25]

What happens then is that whatever was transplanted is rejected and even attacked. There are three types of reactions that can take place: hyperacute reactions, which are fast (usually occur few minutes after the transplant) and happen when the antigens are completely unmatched. The transplanted tissue or organ must be removed immediately – if not it could lead to the death of the person.[25] A case of this is, for example, when a person is given the wrong type of blood.

The second type of adverse reaction is the acute rejection. It may occur shortly after the transplant, anytime up until three months.[25] Lastly, chronic rejection, which develops progressively after years of the immune system attacking the transplant. It is irreversible.[25]

The way in which doctors try to avoid the transplant rejection is by matching as much as possible the antigens between the donor and the person receiving the transplant.[25] In the case of a blood transfusion, by making sure both have the same blood type. With the exception of identical twins however, the match is not perfect.[25] What can be done in these cases is give to the person receiving the transplant medicines that suppress the immune system's reactions to prevent it from attacking the foreign tissue.

Dr Anthony Atala, director of the Wake Forest Institute for Regenerative Medicine has been making manually tissues and organs for over a decade (Figure 6), growing them from patient's own cells.[26-27] For it, he uses a gel-like water-based substance mixed with living cells that has layers of small tunnels from where the cells obtain their necessary nutrients until transplant.[26,28]

Figure 6: Anthony Atala holding a human kidney 3D-printed during a TED talk. (TED, 2011)

In 2016 he already made history by growing and implanting a bladder into a person.[26] In addition to that he grows skin, cartilage, urethras and muscles between other things.[27] Presently, he is faced with a new challenge: regenerating much more complex organs and doing so with the help of a 3D printer, as it would be much more precise.

The printing system receives the name of Integrated Tissue and Organ Printing System (ITOP).[28] Three things are hoped to be achieved with it: cells surviving the printing process, maintaining their structure and the right consistency and developing blood vessels once implanted in a human being.[27]

Progress has already been made towards this – Atala's team recently printed a baby-sized ear that was implanted on a rodent. Once there, it developed blood vessels.[27]

Obviously printing body parts is complicated as even a simple and relatively small structure (as the baby-sized ear that Atala's team printed) has a big number of cells that must receive their vital nutrients by thousands of capillaries.[28] The fact that they were able to overcome this problem is already a good sign and the proof that 3D printed organs might be closer than everybody thinks.

Erik Gatenholm, co-creator of Cellink, a type of bioink created for 3D printing and cell culturing made out of hydrated cellulose nanofibrils and alginate[29] says that within ten years we will start seeing implants in the cartilage field and adds that replacing failing organs by 3D printed ones will most likely occur during our lifetime.[24]

Other examples of advances that are being made in this field of the medical industry include the creation of a 3D human tissue printer operating on a robot[30] and the creation of brain-like tissue by a group of scientists in Australia using bioink containing pluripotent stem cells, similar to embryonic stem cells in the way that they can turn into any other type of cell.[31]

2.4 Design software

Design softwares have been in the market since the 1960s, but back then their price was much higher than it is today.

Their function is to capture the shape of simple physical objects that can be interacted with by reducing them to merely height, width and depth measurements (or the x, y and z coordinates).[7] But a more complex object with round components can become a real challenge as the design file needs to have an extensive set of x, y and z coordinates in order to express each individual curve of the model.[7]

Yet, the fact that all this is done by a computer means that the most difficult part of the design process is automated and, as a result, it is easy for users to experiment with different surface textures and colors[7] being able to save different versions of the same end product.

The good thing about keeping things as a computer file is that all the information can be easily shared with other people, for example, by posting the file on a website and making it downloadable. Then, others can access it with a quick click of their mouse and 3D print whatever it was designed on said file, the only requirement being having a 3D printer or being allowed to use one from their office, university or school.

But while design programs have plenty of advantages, they still have some setbacks, one of them being the fact that, still today, it is impossible to digitally capture a real-life object completely.[7]

2.4.1 Programs for design

Two types of design software can be distinguished:

Solid modelling started in the 1990s and is mostly used by engineers and designers in the industrial field. Users can already pick cubes, cones, cylinders and spheres from a library and combine them easily with the help of the tools available to them.[7]

A great feature of solid modelling is the fact that it can tell those using it if a model will work as intended or not, making it possible to save money on the manufacturing process and, also, making the assembly easier.[7]

Surface modelling, on the contrary, finds its use in the videogame designing industry and graphic companies. In this case, the user is trying to create something that cannot be composed by only basic geometric figures.[7] It is a category of design program that, instead of simplifying an object into x, y and z coordinates, cloaks a virtual net made out of polygonal geometries, each of them corresponding to a data point that the designer can work with, around a certain shape.[7]

It is only needed to take a look at any videogame or animated movie made in the last few years to see just how well this kind of programs are able to capture the world to a surprising level of detail (Figure 7).

Figure 7: Screenshot of the videogame Skyrim, developed by Bethesda Softworks in 2011. (Three Parts Theory, 2011)

Nonetheless, this is also a difficult process as it depends highly on rendering, which is the process of adding shades, colours, movements… to a 3D wireframe so as to create an image as realistic as possible.[32]

2.4.1.1 SolidWorks

SolidWorks is a computer program published by Dassault Systèmes, a corporation formed in 1993 that allows engineers and other professionals to create better and faster 3D designs working with relatively easy-to-use software.[33]

Although it is aimed towards the making of industrial objects[34], it has many applications and not only in the design industry, although this is, obviously, where it is more largely used. In the fashion and sports industry it is used during the development of the product and sometimes also during the manufacturing process.[35] For example, professional athletes require the clothing they use for competitions tested and by simulating it with SolidWorks they save money, time and avoid the problems that arise during manual testing.[34]

Another reason why this program is used in the design industry is that it allows more than one person to make changes to the same file, as it has collaborative tools. This is also why they employ it in the automobile industry – especially manufacturers of spare parts and car brands.[35] Also, it allows them to see how the same car would look in different colours and can run studies so as to know which one would be the best selling model.

But where SolidWorks really shines is the design industry, as previously stated. Architects, sculptors, people working with 3D printers either on their own or as part of a company and other design related professions all use this program.[35] Furthermore, it is employed at universities, as the facility of its use enables the student to get hands on experience with the design process of an object.

Another advantage of using SolidWorks is that whatever it is designed in the program can be printed as easily as it would be to print a normal document in a regular printer.[36] However, while designing an object, it is important to keep in mind that the model on the screen, once printed, will be subjected to physical rules such as gravity[34] which is why sometimes extra support should be added.

Other things to keep in mind are that the different bodies of the model should not intercept with one another, that the file's size should not be higher than a certain limit and that all the elements, without exception, require a thickness value.

Finally, SolidWorks can output various formats for 3D printing: .stl, 3MF and AMF (Additive Manufacturing File Format). While the first one is widely accepted, the two latter give extra information about the model in question and do not require the user to define things such as the orientation, materials, colours, position in relation to the 3D printer…[36]

2.4.1.2 Others: scanning

Another way to transform real, physical objects into digital ones is by using optical scans (Figures 8 & 9), which is a different way of capturing the shape and dimensions of something in x, y and z coordinates.[7] This is especially useful when what we want to print is something for which there is no existing designs, such as complex shapes that might be difficult to create with the use of design software.[7]

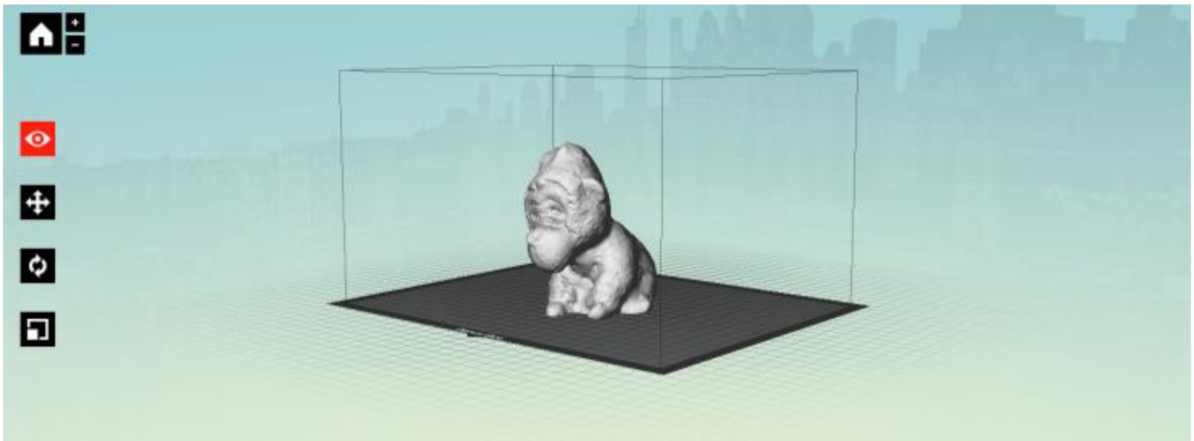

Figure 8: Scanned version of a stuffed gorilla done by using the app 123D Catch before it was discontinued.

Figure 9: Real stuffed gorilla.

While some may think that designing files from scratch is better as it allows more freedom when it comes to editing, replicating and copying, this is not exactly true. Said actions can be performed in scanned files all the same.[7] In fact, there are programs made particularly to help with this process.

One of those programs is Meshmixer, in which it is extremely easy to "clean-up" a 3D scan, as it can easily happen that while someone scans an object, they scan also other components – if the object is lying on a table, the table or other items lying around (a glass, a piece of paper, a pen…). It is Autodesk software, mostly used to prepare and edit .stl and .obj files (it can also be used for creating models using mesh combinations), which can be used for free.[37] Between its tools, one can find 3D sculpting and surface stamping, hollowing (which can help saving time and material), branching support structures for 3D printing, plane cuts, mirroring, interior tubes and channels, automatic alignment of surfaces and automatic print bed orientation optimization as well as many others.[37]

After downloading, installing and starting Meshmixer the user needs to import whatever file needs to be optimized. While using it, the 3D printer that will be used to print the end result can be chosen from their database or, if not in there, be inputted manually.

All in all, for those who do not know very much about designing but still want to create their own files, scanning data allows them to enjoy the 3D printing process as much as anybody else. It might even be easier for them due to the existence of smartphone apps such as Qlone, Trnio, or Scann3D.

These apps all mostly follow the same procedure: whatever it is the user wants to scan must be placed on a flat surface, if possible, with no other objects around it as when the scanner is capturing the dimensions of the object, it may accidentally include other things as well (which is what programs such as Meshmixer are for – some of these apps also have editing programs of their own). Afterwards, as many pictures as possible and from as many angles thinkable need to be taken with the phone camera, so that the object is captured reliably. This might be troublesome for objects which are not supposed to have a flat surface – in this case, the object can be tried to be captured in the air (with someone holding it, for example), although the 3D scan will probably need more work once this is done.

Some apps such as Qlone do not allow this as they require the printing of a mat from their website in which the object the person wishes to scan is placed. On the other hand, this avoids most of the post-scanning edition, as the capture is done more cleanly.

The pictures should then be processed and within no time the user should have a design they can access, share and tweak as they wish.

2.5 Analysis methods

In order to analyse something, the first thing that is required is to collect data. For that, we research. Both, methods of analysis and research can be fundamentally divided into two categories: qualitative and quantitative.

Nature of research varies due to the fact that different works have different objectives.[38] These different objectives require distinct approaches and methods, which is where the previously explained division comes into play. Although qualitative and quantitative methods are considered to be completely unrelated, their objectives and applications converge more often than not.[39]

2.5.1 Qualitative analysis

It is used mainly so as to understand the reasons behind certain actions and motivations for doing something – it also provides information surrounding the circumstances of a problem.[39]

Complete, detailed descriptions and non-numerical and non-statistical findings are usually the result of qualitative methods of research and analysis.[38,40] A problem, however, which arises with this is that the resulting data cannot be applicable with the same conviction as with quantitative methods due to the fact that the facts are obtained through more unstructured and more flexible techniques such as group discussions or individual interviews.[39] To summarize, no conclusions can be derived from the obtained information and it cannot be used to make generalizations but it does give background and understanding on whatever is being researched/analysed and helps with further decision making.[39]

Focusing only on analysis, qualitative methods try to make sense of huge amounts of information that do not all come from the same source in order to answer a particular question.[38] It relies mainly on other people’s impressions, and as such, it is important that the information is presented in a structured and clear way.[38]

In the process of analysing qualitative data, three different parts can be distinguished: reduction of data (which involves reading all the information and compressing it into key topics and themes that can be useful), abstraction of themes from the reduced data and last but not least, organization of said themes in order to get a somewhat clear answer to a precise research question.[38]

2.5.2 Quantitative analysis

Its main purpose is the quantification of numerical information.[39] Results obtained with this method, contrary to what happened with qualitative analysis, can be generalized and are both statistical and numerical, also using graphics and tables to better present and illustrate the findings.[38]

Methods by which quantitative data can be obtained are structured and inflexible and include surveys and questionnaires, measurements, records, assessments… They allow the analyser to widen their knowledge regarding part of the population of an area and, afterwards, generalize about the total population within a certain limit.[38]

Making quantitative data become useful information can be done with the help of statistics – by using features such as categorical and numerical data, percentages proportions, means and medians, it is easy to summarize and find mathematical differences between various groups of data.[38]

Typically, however, quantitative and qualitative methods are combined.[39] They are usually compared and contrasted which usually gives a broader view of whatever it is being studied and confirm or deny initial assumptions the analyser might have.[38]

A very important disadvantage of quantitative data however is that it is easy to over-generalize results[38] – for example, saying something is ideal and would work perfectly fine for every person in the world when only a hundred people have filled in a survey. Furthermore, conclusions and possible advices should not in any way be based on subjective opinions but only on the information gathered.[38]

3. Method

3.1 Design of a prosthetic arm

After writing the literature review and therefore researching the different 3D-printed prosthesis available nowadays, it was decided to design a prosthetic arm greatly inspired by those made by the members of Enabling the Future. Therefore, the arm designed for this thesis will not fully resemble a real one, looking more bionic-like. There are different types of prosthesis for different types of amputations – a person could be missing their whole arm or just the forearm[41]. In the latter case they are usually left with a stump a bit below the elbow. This is the case the report will be focusing on.

The arm will be fully designed by SolidWorks and it would need to meet the following requirements:

- Fit a woman of around twenty years of age, average height and average weight – however, this point in particular is not of great importance because by doing the design in SolidWorks, its measurements could easily and rapidly be changed to fit whoever needed it.
- It should be as light as possible so that the user feels comfortable with it.
- It should be able to perform basic movements. It is important to note, nonetheless, that the prosthesis produced for this thesis will most likely not move at all as the designer has no knowledge of how to program a circuit for this particular goal.
- Preferably as economic as possible in terms of materials as it was previously discussed that one of the biggest problems of prosthesis is their price.
- It should be able to lift some weight. Once the prosthesis is completed a simulation will be run also in SolidWorks applying the forces correspondent to 100 grams and 1 kg and see what the reactions of the designed part are.

Before starting with the design and in order to fulfil the goals stated above, the movements of a working arm must be studied. While most likely no prosthesis will be able to completely replicate them in the near future, the way it moves should be as similar as possible, allowing the user to close and open the hand and even grab some lightweight stuff.

Another aspect to be taken into account is the measurements of the prosthesis. While they may not be the most crucial thing, it is important that they make sense, meaning by this that the size of the fingers, hand and forearm of the prosthesis match those of the other arm (assuming the person in question is only lacking one upper limb) or those of a person with the same physical characteristics as the user (assuming they have lost both arms).

The prosthesis produced for this thesis project is based on the writer's right arm approximate measurements, which can be found in Figures 10, 11, 12, 13 & 14. Furthermore, in those figures is also illustrated the way the arm should behave when completely finished and with an electric circuit or mechanism of some sort that allows it to perform movements.

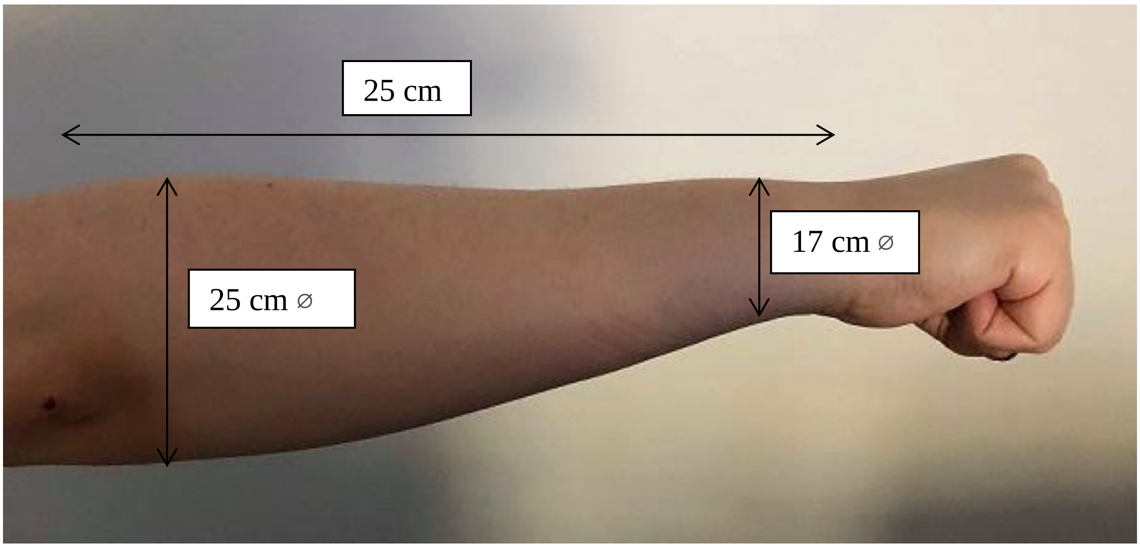

Figure 10: Right arm with a closed hand, facing downwards. Also, the measurements for the forearm are showed here.

Figure 11: Right arm with an open hand. The hand is facing downwards**.**

Figure 12: Right arm with an open hand. The hand is facing upwards.

Figure 13: Right arm with a closed hand. The hand is facing upwards.

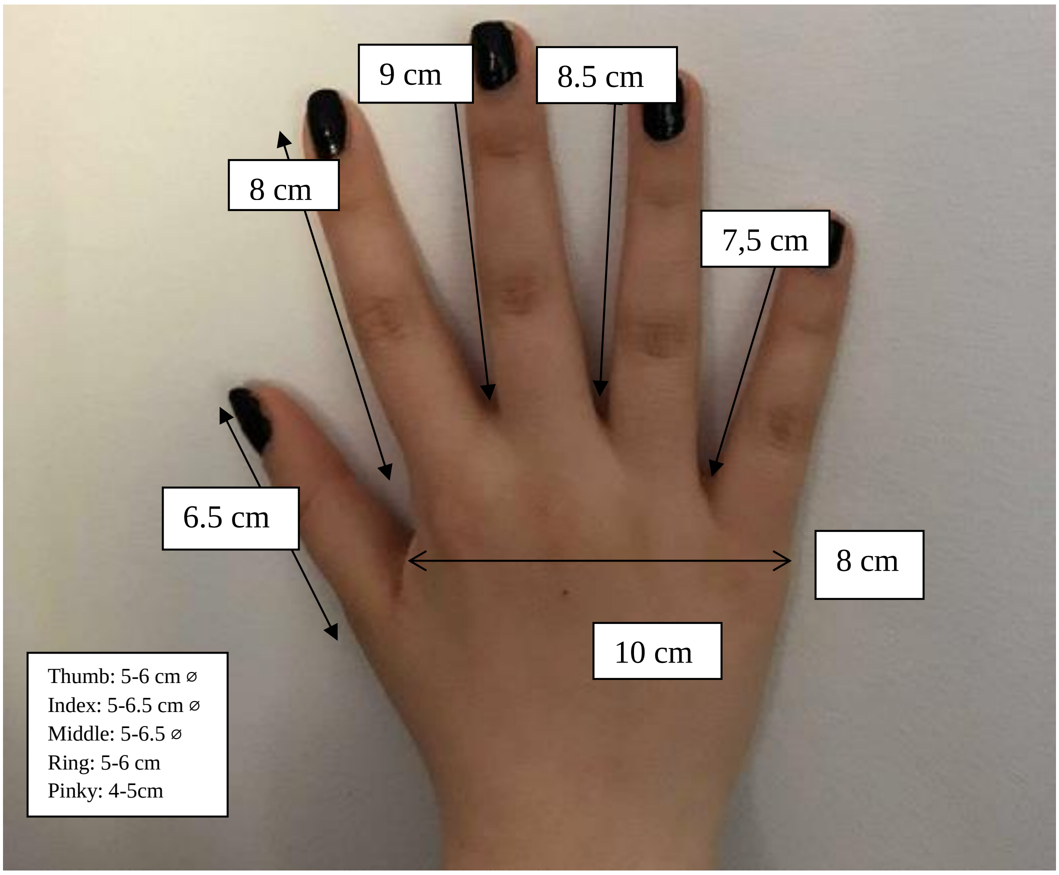

Figure 14: Right hand. Measurements for the palm and fingers are indicated.

3.2 Production of the arm

The arm will be produced using SolidWorks.

As stated before, this thesis will focus on a person who lost their right arm and is left with a stump below the elbow, which is why the forearm will be the first part to be created.

For it, first thing that was done is create reference geometry, a plane to be exact, 25 cm apart from the original front plane. Afterwards a centrepoint straight slot was created with the already taken measurements of the beginning and end of the forearm in both planes. It is important that both have the exact same centre.

Once the two straight slots were drawn, they were joined using the feature lofted boss/base, obtaining that way the first part of the prosthesis, which may or may not be subjected to modifications later on (Figure 15).

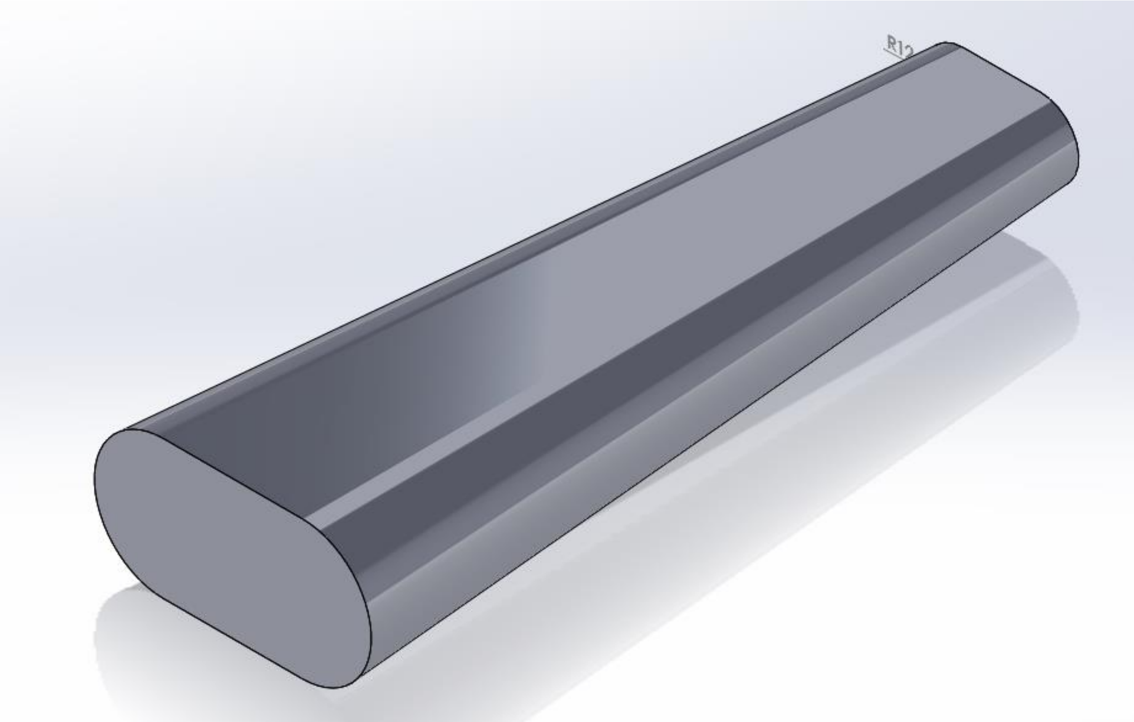

Figure 15: Design of the forearm, created by SolidWorks with two centerpoint straight slots and reference geometry. Isometric view.

Following this, the hand was created. The same technique that for the forearm was used.

Again, a reference geometry plane was created, this time 35 cm from the front plane, so that there is 10 cm between what is supposed to be the wrist and the end of the hand (the fingers are excluded because they will be added later on). Another centrepoint straight slot was sketched with the measurements of the hands and joined to the wrist by using the feature lofted boss/base.

As it can be derived from the way the drawing is done so far, the forearm and the hand form a unique part to which the fingers will be joined to form an assembly.

The resulting product is illustrated in Figure 16.

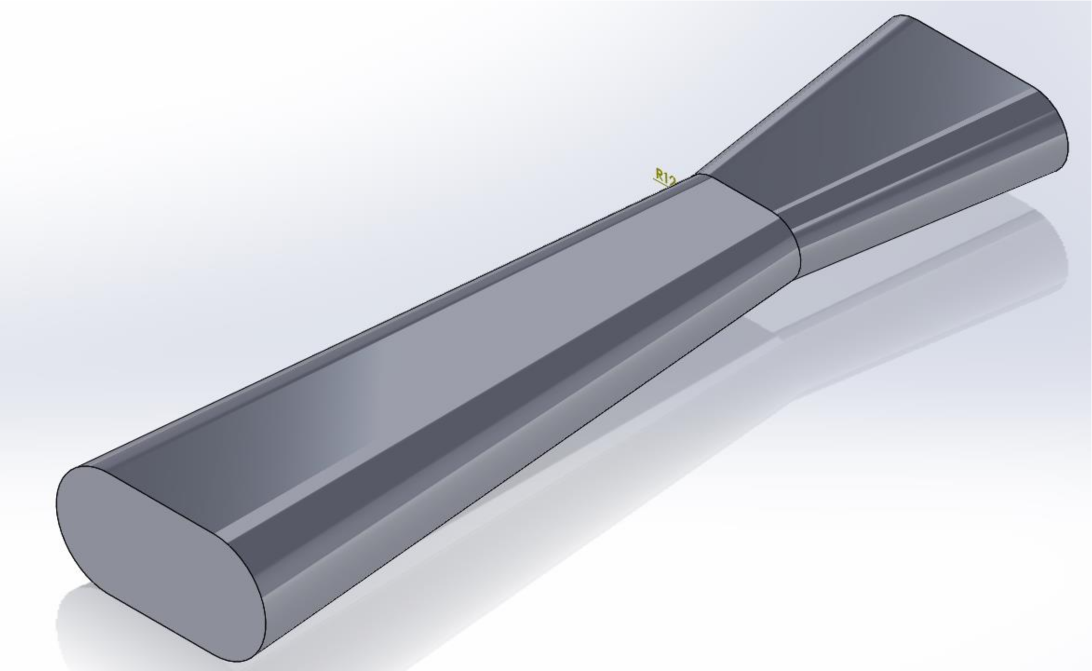

Figure 16: Design of the forearm and the arm, created by SolidWorks using three centrepoint straight slots and reference geometry. Isometric view.

A change was performed after creating this structure, because it can clearly be noticed when one looks at the palm of a hand that it is not completely flat, which is why an extruded cut of about 1 mm was performed, the product then being what can be found in Figure 17.

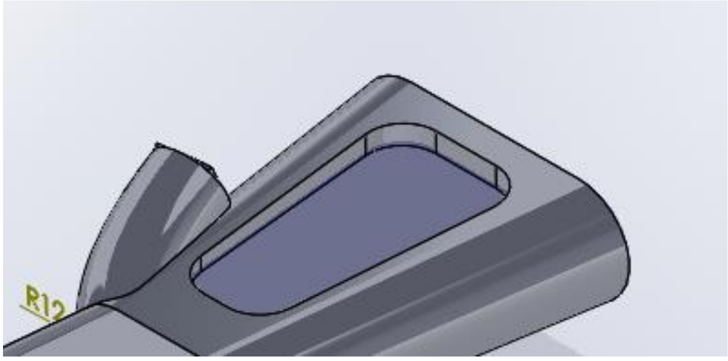

Figure 17: Detail of the palm of the hand, now with an extruded cut of about 1 mm and fillets around the edges. Done in SolidWorks. Isometric view.

The original idea was to add the thumb (previously created as a different part) to the side of the palm via mate. However, when this was done it was perceived that that would greatly difficult the mobility of the thumb as it would constantly be clashing with the structure it is mated to and that this finger should be slightly in front of the others to facilitate gripping objects.

This was the reason why a reference plane was created somewhere along the middle of the palm. A circle was then drawn there and the command swept boss/base was used to join said circle with the part of the design representing the wrist. The idea came from watching other similar designs and video tutorials in YouTube, such as that uploaded by a channel called DT Works on October 30th, 2017.[42]

The result of this can be seen in Figure 18.

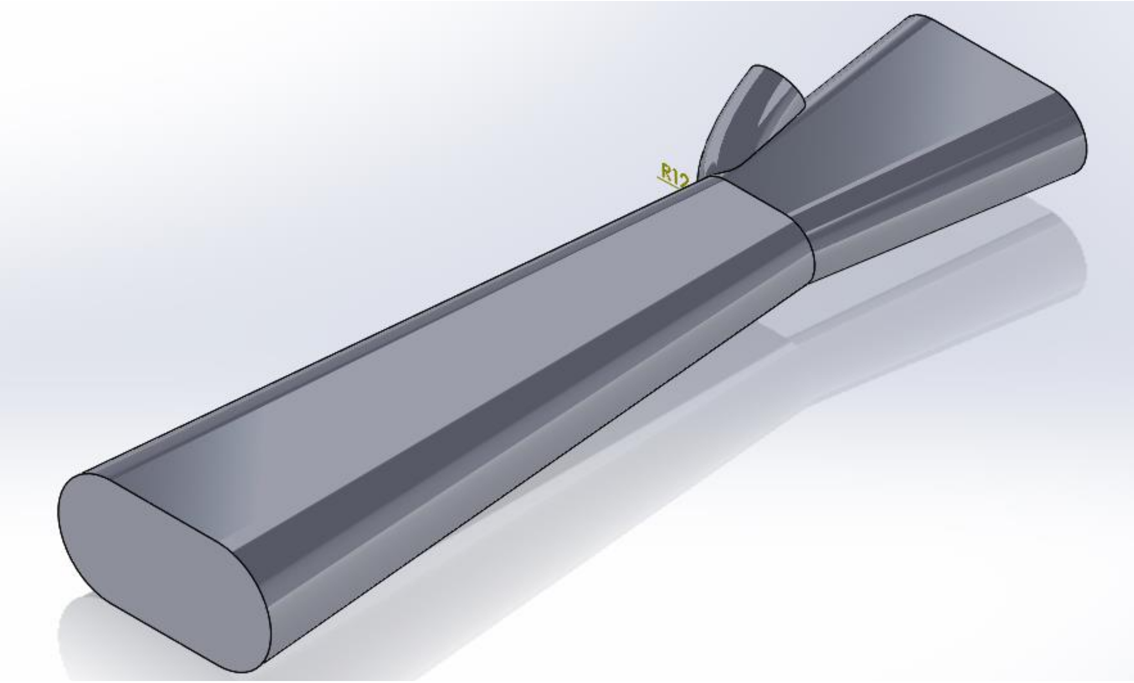

Figure 18: Design of the forearm and the arm as well as the first part of the thumb, created using SolidWorks using the swept boss/base command. Isometric view.

Moving on to the fingers. As previously stated they were done as a different part than the forearm, palm and first part of the thumb. Fingers are supposed to flex in three different positions – which is why they will each be composed of three different parts, joined together by small flexible structures on the sides.

The first, middle and top part of the fingers are in Figures 19, 20 and 21. The place where the small flexible structures will be located can also be appreciated in the images.

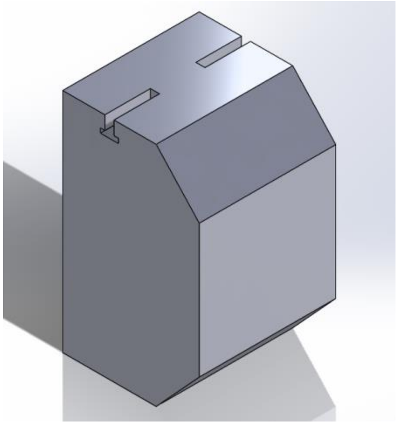

Figure 19: First part of the finger (in this particular case the index), done in SolidWorks. Isometric view.

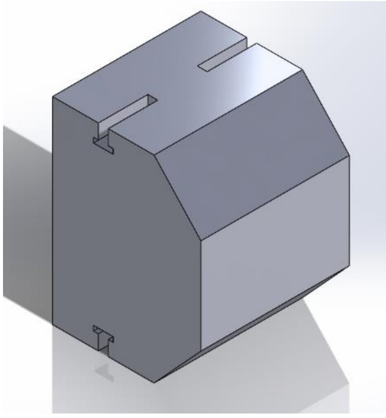

Figure 20: Middle part of the finger, done in SolidWorks. Isometric view.

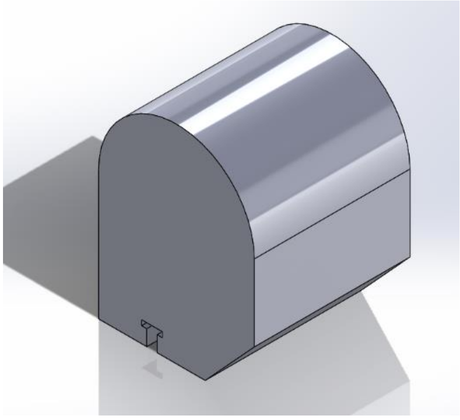

Figure 21: Top part of the finger, done in SolidWorks. Isometric view.

In addition to that it should be mentioned that as fingers do not all have the same length (the middle finger being longer than the index and the ring finger and the pinky or little finger being the smallest) and the intention is to keep the design as close to reality as possible in regards to dimensions, the measurements for the first part of the fingers vary: the index and ring finger have the same measurements, the middle finger is 5 mm longer than them and the little finger 5 mm shorter.

A better view of the small flexible structure supposed to join each part of the fingers together is provided in Figure 22.

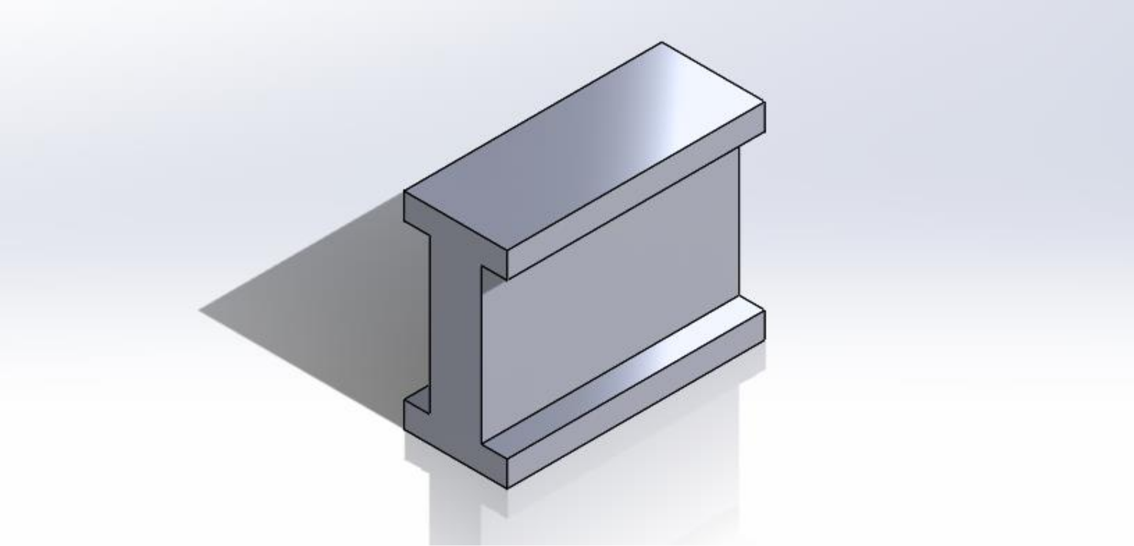

Figure 22: Small structure that will be printed with a flexible material in order to join each part of the fingers together but still allow their movements. Done in SolidWorks. Isometric view.

Going back to the thumb, it was be done in the same way as the rest of the fingers with the exception that it needs to only be able to flex in two different positions. Which is why it only consisted of a first part and a top part.

However, this meant one more change needed to be performed on the stump of the thumb due to the fact that while it is round, the first part of the finger is square in shape. A reference plane was created 1 mm away from the stump's top face and a square was drawn following the measurements used for the finger. Subsequently the lofted boss/base was used. Result of this can be seen in Figure 23.

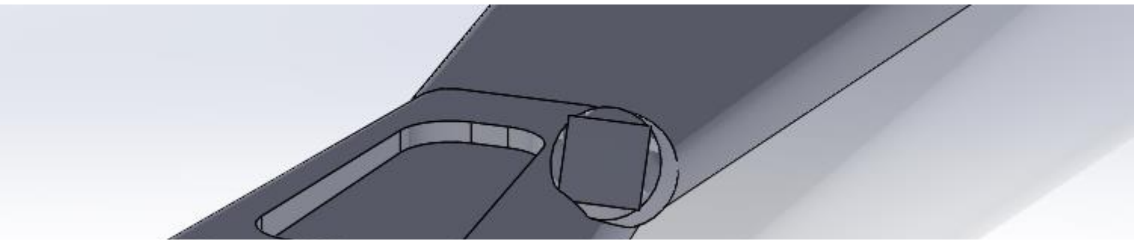

Figure 23: Picture of the stump of the thumb after changes. Created in SolidWorks. Back view from the top.

After this all the parts were done and what was left was thinking of a way to join them with the palm. Similarly to the small structure that joins each part of the fingers together and that will be 3D printed with a flexible material, another small structure to be printed with the same kind of material was created by drawing and extruding a square of 2 mm on each side with a wider part on both, the top and the bottom of the figure of 1 mm more on every side. To further comprehend, one can just look at Figure 24.

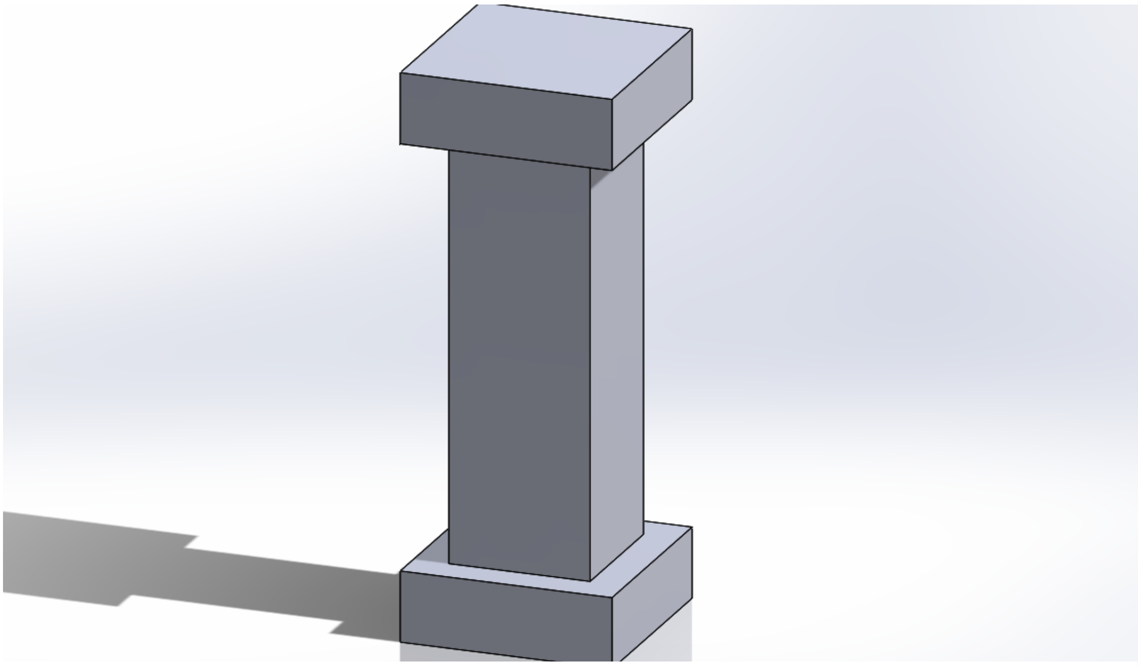

Figure 24: Structure that joins the fingers to the palm of the hand and also, the thumb to its stump. Created with SolidWorks. Isometric view.

For it to fit, holes of those dimensions will be added both in the palm of the hand and the first part of the thumb. (Figure 25).

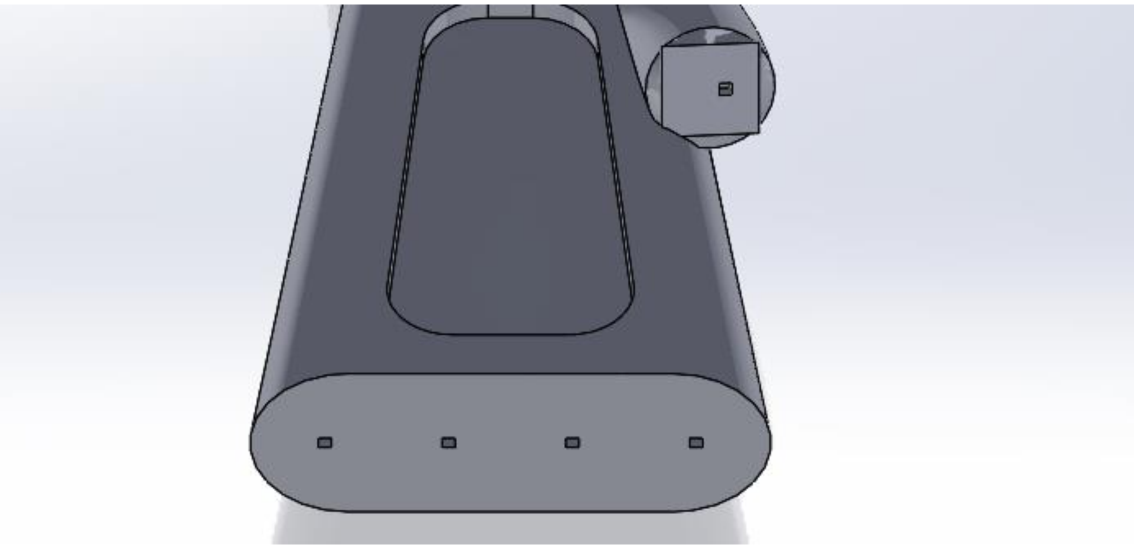

Figure 25: Holes in the palm of the hand and the first part of the thumb. In the case of the palm, the holes are positioned so that there is 4 mm between the fingers, each of them being 1.5 mm of width. Done with SolidWorks. Back view from the top.

With that, the design of the prosthetic arm is ready (Figures 26 & 27). The idea regarding printing is that the forearm, hand and first part of the thumb get printed together. Each part of the fingers should be printed separately, as should the structures used to join them together and the first part of them with the palm.

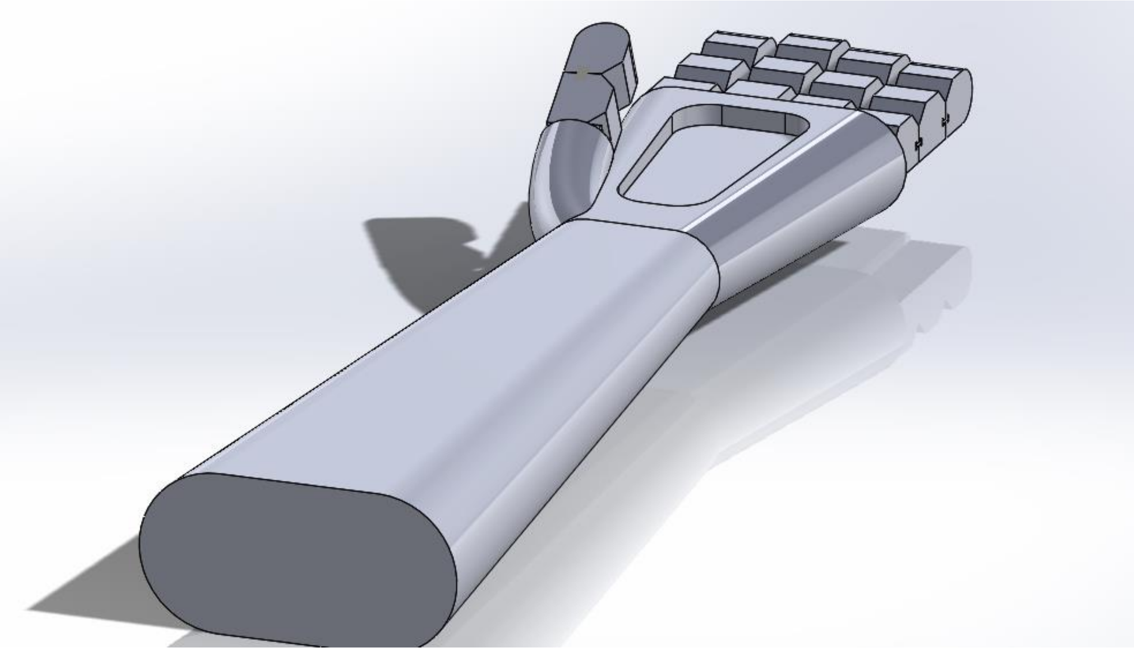

Figure 26: Ready version of the prosthetic arm. Done in SolidWorks. Isometric view.

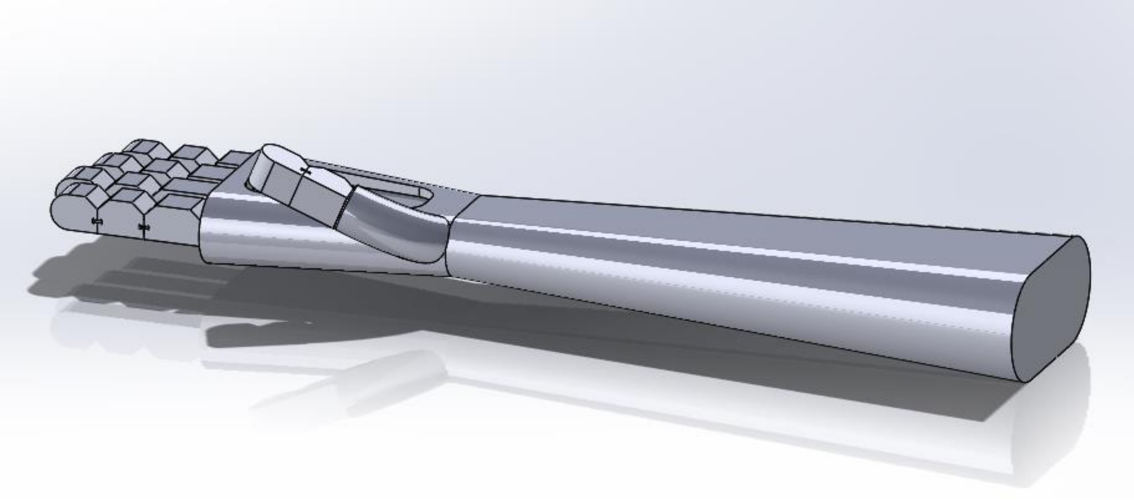

Figure 27: Another picture of the ready version of the prosthetic arm done with SolidWorks, this time seen from the side.

As said previously, the arm is not able to move on its own due to the fact that the writer does not have enough knowledge on how to build a circuit that enables those actions.

However, if it were to move, the forearm and hand would be made hollow and small holes would be cut into each part of the fingers. Some sort of thread or string (of a strong material, so it would not break) would go through those holes and be pulled by a mechanism that would be built inside of the forearm, making it possible for the fingers to bent (an example of how they are supposed to move, without any connectors as they cannot be made to stretch in SolidWorks, is on Figures 28 & 29) and therefore, grab and hold objects between other things.

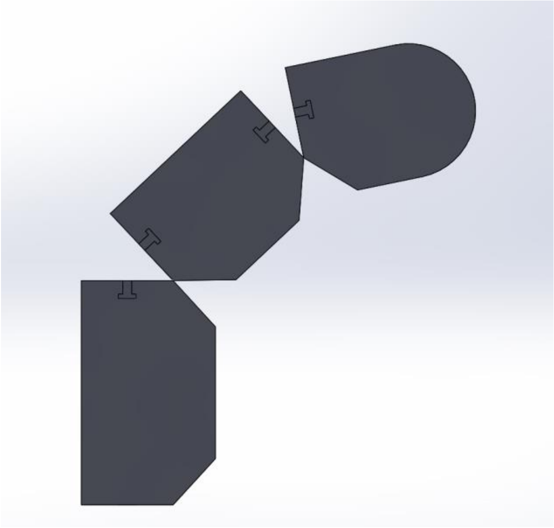

Figure 28: Bent finger from the side

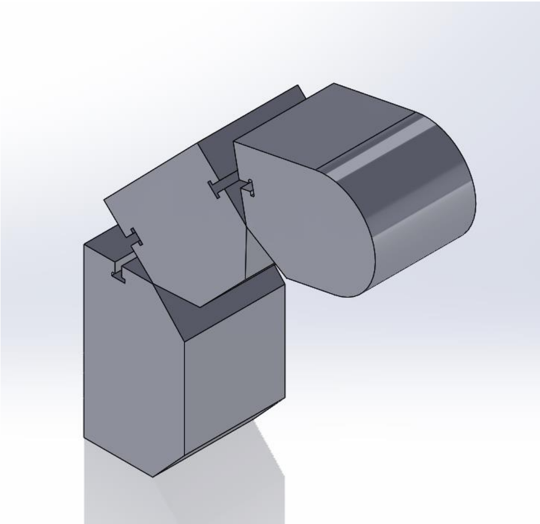

Figure 29: Bent finger from the top right side

This same way of making the prosthetic hand move is used by Enabling the Future on many of their most used designs[43].

3.3 Testing

Testing will be done by running a Solidwork simulation on the piece. For that, however, the material with which the prosthesis will be printed should be decided.

The idea is to print the different parts of the prosthetic arm with PLA as it is the main thermoplastic used by the MakerBot printers owned by Arcada. However, for the small connectors that, as repeated many times, should be flexible, Formlabs' Flexible Resin will be the chosen material.

Apart from that, PLA is made out of renewable sources such as corn starch and sugar cane[44] (materials the world will most likely not run out of easily as opposed to petroleum and others) and it could be taken to any industrial composting facility to biodegrade. However, the conditions for it to degrade are not given anywhere else[44], which means that if disposed of incorrectly, PLA is no better than any other plastic in that area.

Also, the life of this product could be easily extended by machines like the Filabot, that transform any plastic – not exclusively previously 3D printed products as it should also work with water bottles and plastic wrappers[44], into printing material, ready to use from the first moment.

At first, during the simulation, loads going from 1 kg to 5 kg were going to be applied. Nevertheless it was decided only to apply loads of 100 grams and 1 kg, after reading articles versing on the topic of people receiving 3D printed prostheses – specially the one cited in the literature review about a Spanish kid receiving one from a teacher and four students[18], in which he happens to mention that he could easily hold a flower and a package of bubble-gum but not a package of salami in the supermarket as it “weighted too much”.

In order to simplify the simulation, it was done on only the parts of the arm that would support most of the weight: the forearm and hand as the fingers would mainly serve of support. A custom material with PLA properties was created, as fixed geometry the forearm and the hand were both selected and a load of 1 N (correspondent to approximately 100 grams) was applied in what would be the palm of the hand. The results of the simulation can be found in Figure 29.

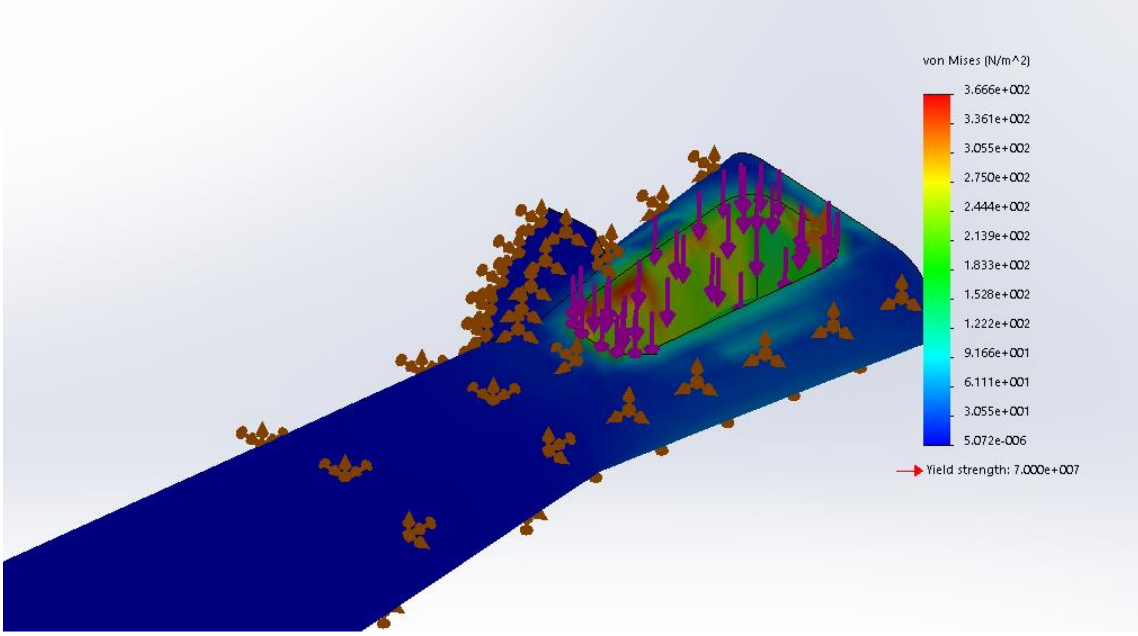

Figure 29: Results of the first simulation. They are believed to be incorrect due to the fact that the extruded cut of 1 mm in the palm of the prosthetic hand could not be set as fixed geometry.

It can be seen there is a great deformation on the extruded cut of 1 mm that was done in the palm of the hand. The reason for this to happen is believed to be the fact that this face cannot be set as fixed geometry, and therefore seems to deform here while in real life it most likely will not.

A second simulation was run with a load of 10 N, which corresponds approximately to 1 kg. Similar results were obtained, which can be seen in Figure 30.

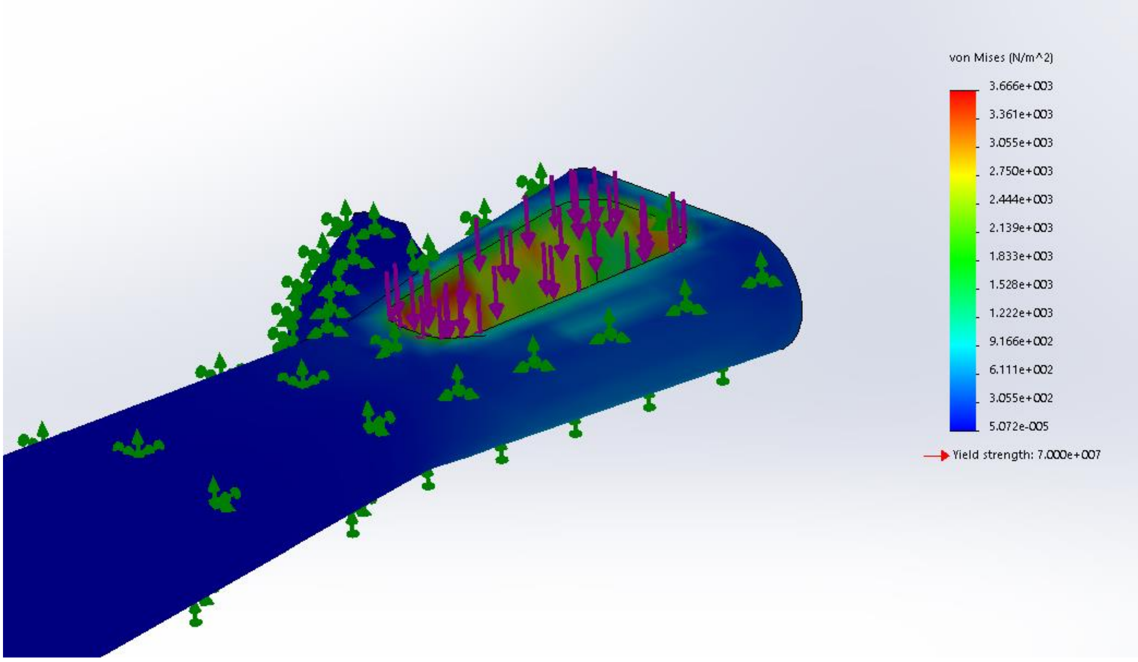

Figure 30: Results of the second simulation. The same problem as in Figure 28 – the results seem to be incorrect due to the fact that the extruded cut of 1 mm in the palm of the prosthetic hand could not be set as fixed geometry.

Again, the writer believes the prosthesis will almost certainly not behave like this in real life, which is something that could be proven once and if the design is ever printed at full scale and tested then.

3.4 3D Scanning

A question arose while the prosthetic arm was being modelled – could this be done by scanning the user’s other arm (in case they still have it) or the arm of someone with a similar body built? The answer, in principle, is yes. However whether this would look better or worse than a design made on SolidWorks from scratch is up to debate.

First of all, programs that use scanning as a way of creating 3D models use mainly one of two methods: a 3D scanner in which the object is deposited on it and rotated so that all the possible angles are considered or the person creating the model has to take pictures of the real life object usually (and for better results) while it lays on a flat surface.

Both options create problems. The former being that a person cannot possibly put their own arm in a scanner and rotate it in the same ways as it would be done with, for example, an inanimate item of some sort. The latter option’s main concern is that the palm of the hand would just be a flat surface and that would not help whoever uses the arm in the process of grabbing and/or lifting any kind of object.

A possible way in which both these situations would be dealt with effectively is by making with clay, silicone, alginate or some similar material, a mould of the arm. Then this object could be photographed easier and, if the scanner in question was big enough, would allow itself to be scanned.

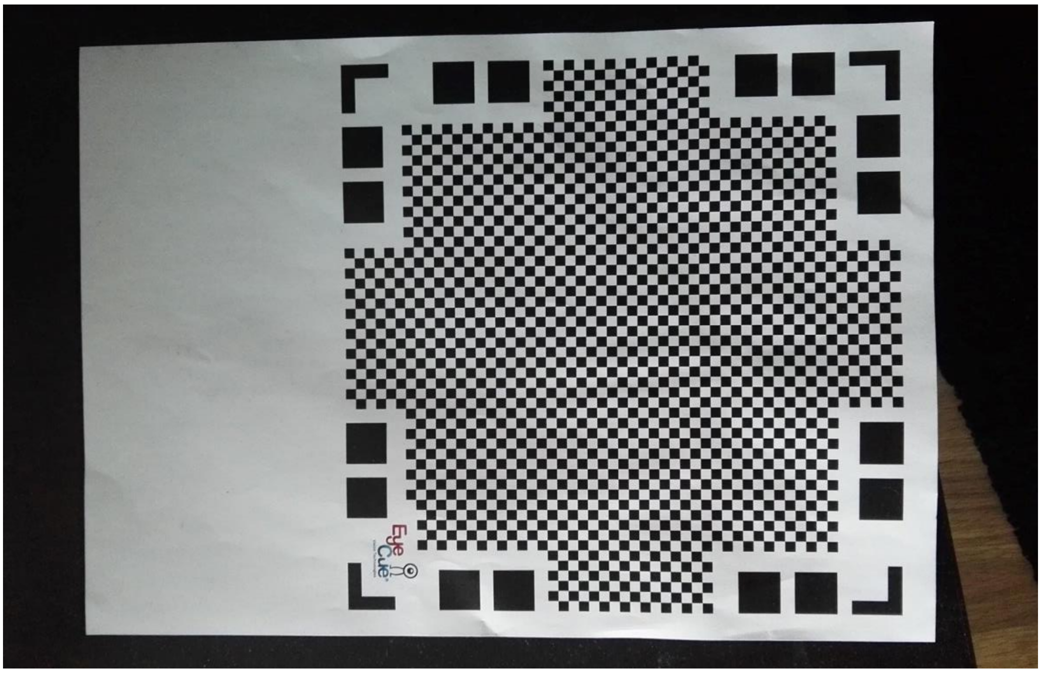

Figure 31: Mat that has to be downloaded and printed in order to work with Qlone.

However, 3D scanning as a whole creates another problem – the fact that when an object is scanned whether this is done with a scanner or by taking pictures of it with a camera or phone, the design is just one part. And as one part, the fingers of a prosthetic arm done by this method would not be able to bend unless changes are performed by transferring the model to SolidWorks or some other editing program. Another option would be to scan each phalange of the finger separately and then join them, each being parts of a bigger design. However, an appropriate way to put together each part of the finger should be found for this to work.

To try it out, the writer downloaded the application Qlone. The reasons for choosing this app are mainly three: first, it is one of the few scanning apps available for Android, it is free and seemed relatively easy to use for a person who does not have a lot of previous experience regarding scanners, at least according to the fairly positive reviews.

This app requires the user to download and print a mat, which can be seen in Figure 31, and place the desired object in the middle of it. But first, the phone camera needs to be calibrated. This is done by simply capturing the mat by rotating the phone from different angles (front, sides, back and top generally speaking). Once the camera is ready, the scanning process can start.

A nail polish bottle was the first object to be scanned, with the intention of getting familiar with the app. The object was placed in the middle of the mat and the phone was rotated around it to get all the geometry realiably. It took a long time due to the fact that it was required for the capture to be valid that the four corners of the mat were always visible. The original object can be seen in Figure 32 and the end result in Figure 33.

While the overall shape is more or less the correct one, at least on the left side, there is obvious disparities on how both objects look. Nonetheless, it should be mentioned that the design can be exported and turned into an obj. and stl. file, so it could be worked around in Meshmixer to get a more pleasing result. Yet, this service is not offered for free.


Figure 32: Original object

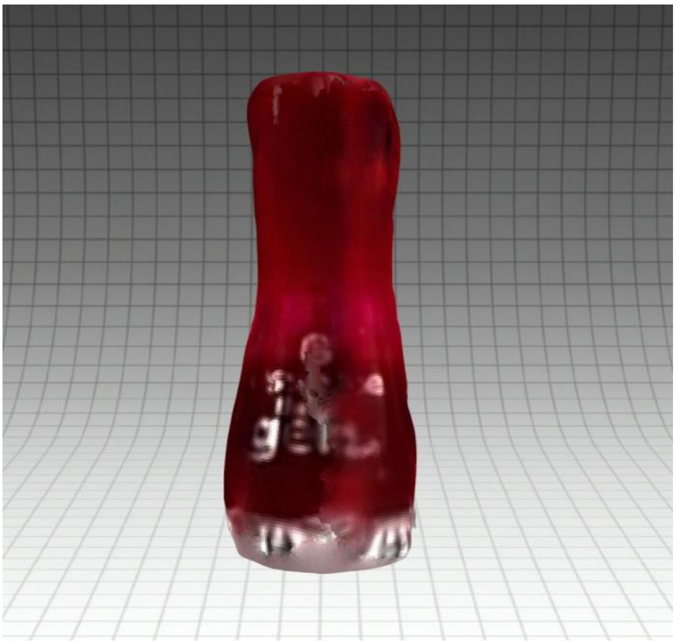
Figure 33: Scanned object

Anyway, the next step was trying to scan a hand, not the full arm because due to the size of the mat, it would not fit. Withal, this did not work either as the hand was attached to someone's body and could not really be placed in the middle of the mat without covering the corners of it, which, as was noted when scanning the nail polish bottle, need to be perfectly visible in order for the scanner to be able to capture the geometry. Even if this could be done, when taking pictures from the left side, for example, the right side corners would not be visible at all due to the size of an adult's hand.

Other apps could be tried, as they all do not give the same results – the proof of it is this same report's literature review where a stuffed animal was scanned with the app 123D Catch back in 2016 and much better results were obtained. Trnio[46], an app that apparently seems to be among the best, requires no mats, is almost free (0.99 cents) and is only available for iPhone users[46] and ReCap Photo (Autodesk's replacement for 123D Catch and ReCap) in which pictures are uploaded to the software and a design is generated after some time were the writer's other options.

ReCap Photo however, did not yield the expected results. As a model, and to avoid the problems that appeared when trying Qlone, a model of a hand found in Arcada's Chemistry lab in D3 and belonging to the health department was used. Pictures were taken of the whole hand, from every angle possible. What came out of it can be found in Figure 34.

Figure 34: Model of scanned hand with ReCap Photo

What can be seen from the picture is that the object barely resembles a hand at all. Possible reasons for this might be the photos being out of order or the quality and light of them not being good enough.

This meant that trying Trnio was the next step. The way in which it works was very similar to Qlone – the user just needs to take pictures of the object they want, from whatever angles they want, but as previously stated they have more freedom while doing it since no mat for reference is required. The writer was able to obtain a nice hand-like model doing this but it required the collaboration of two people: one to place their hand on a solid surface (scanning a hand in the air gave a shaky model as it is very hard for anyone to stay still for the amount of time needed to take the pictures) and the other to photograph that person’s hand from right to left. The process was repeated several times until the results were pleasing (Figure 35).

Figure 35: Hand scanned using Trnio

While there was a lot of cleaning to do as the app also scanned the surface the hand was placed on, the model looked significantly better than the previous two. It could, most likely, be improved further (using natural light or a pricier scanner which would most likely give better results, for example) but for a phone app it looked more than decent. The design was uploaded from the app straight to Sketchfab and from there downloaded as an obj. file. The reason for opening the design in this platform is because of Trnio's partnership with it[47] as the file could very well be sent to the user by email but it would only be available for a short, limited time while in Sketchfab it could be accessible whenever. There was also the possibility of using Meshlab or Blender to view the scan[48]. In any case, whether the user had chosen the option of sending the file to their email or opening it in either Meshlab or Blender instead of exporting it to Sketchfab, the file they would have received would have been in .PLY format.[48]

The file was opened to Meshmixer where it was cleaned using the Select, Invert and Delete tools. The wanted part was selected, and then this selection was inverted so that everything but the wanted part was. Afterwards, whatever was chosen last was erased, and the process (illustrated in Figures 36 and 37) ended with a model that looked very much like a hand.

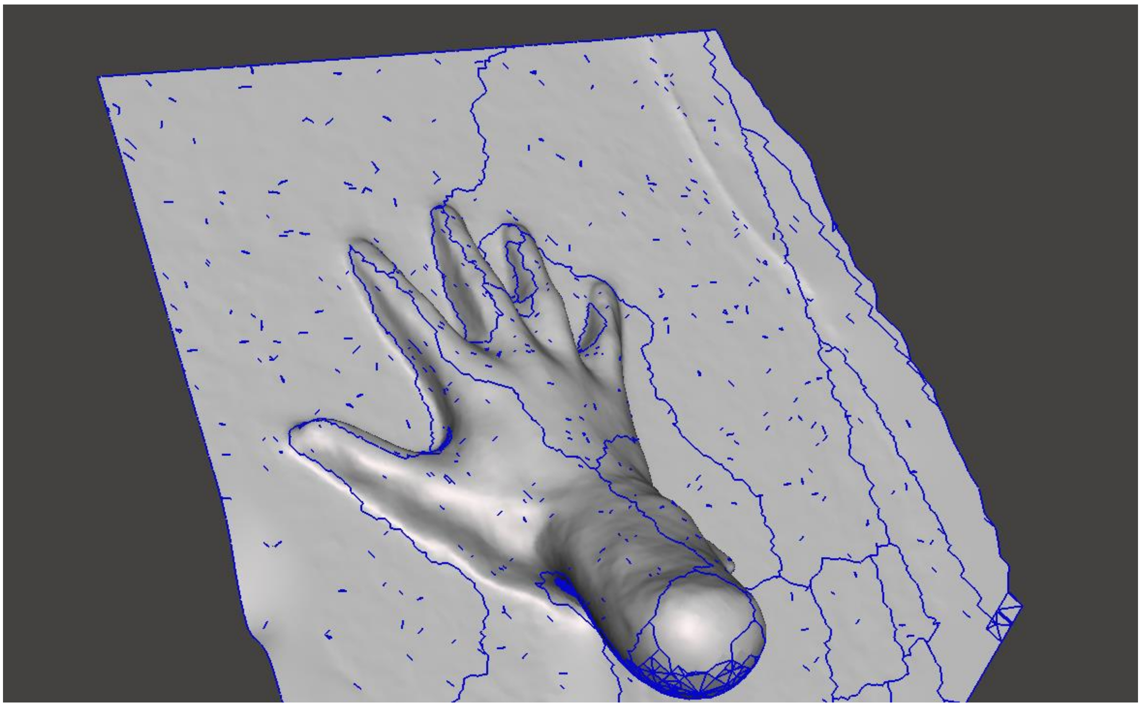

Figure 36: Scan of the hand without any modifications in Meshmixer

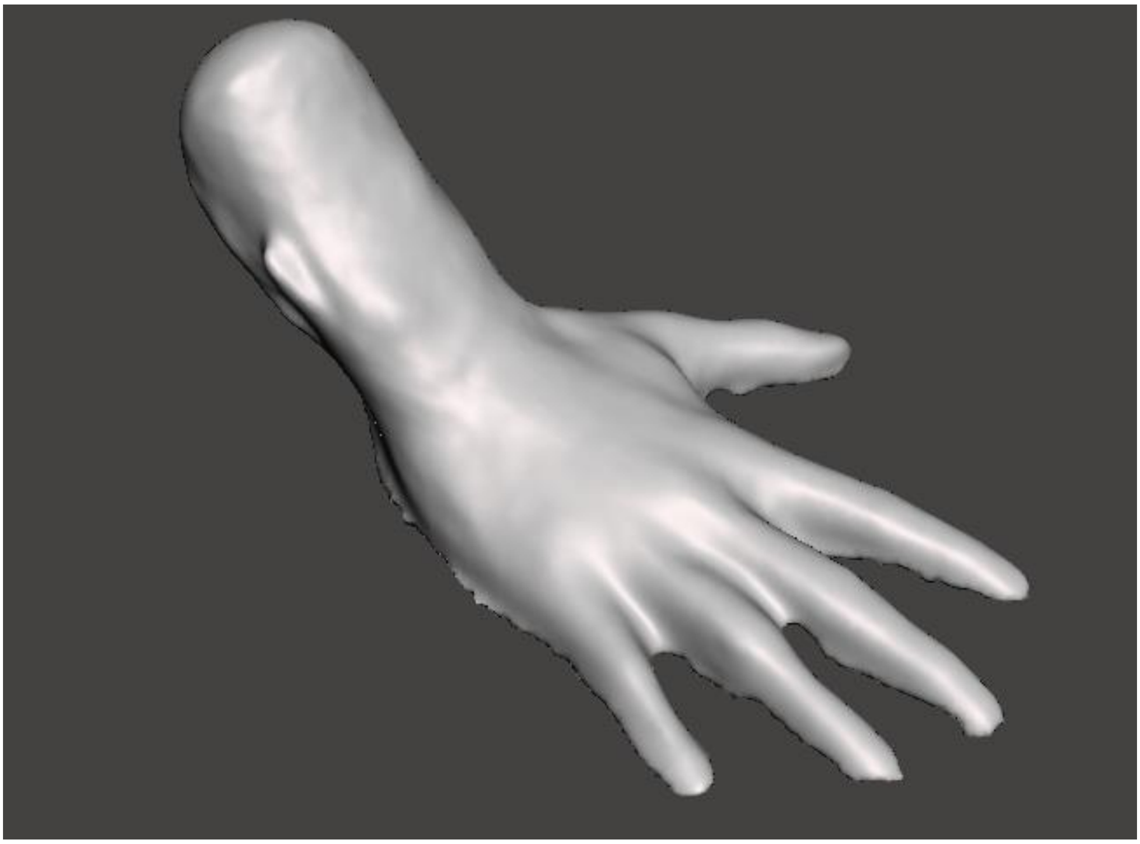

Figure 37: Scan of the hand after deleting the unnecessary parts

There was only one problem found with this model, a big one, however, and it was the bottom of the hand. Due to the fact that the pictures of the real hand were taken from the top and right and left sides, the index, middle and ring finger were not really delimited in terms of depth as opposite to the pinky and thumb, which is why when clearing the area the hand was placed on, a big piece of those fingers was taken away. This can clearly be appreciated in Figure 38. It was tried to make the bottom flat using the Plane Cut tool, nonetheless, making it completely flat left the fingers looking way too short for an adult hand making the hand not look realistic at all which was the primary purpose of scanning. The design could be opened and edited in SolidWorks where it was thought this problem could be solved. Nonetheless, the shape of the fingers was not completely geometrical and it could not be replicated with the available tools, not even with the use of splines.

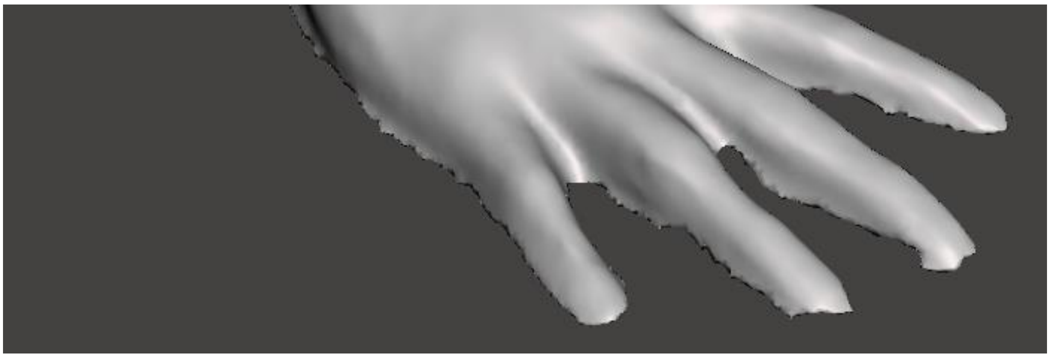

Figure 38: Picture in which it can clearly be seen the missing area of the index, middle and ring finger

4. Analysing the ethics of 3D printed organs and prosthesis

The ethics of 3D printed organs and prosthesis will be analysed using a mix of two different research methods – qualitative and quantitative.

For the analysis, a survey will be produced both in Spanish and English for 190 people to complete it. In it, they will give answers to different questions related to the subject which would allow for the production of numerical values and graphics and tables to further illustrate what is the general opinion of these people.

Due to the fact that the survey will be done in two different languages it could also be a way of comparing the believes of two different groups of people – those who speak Spanish and most likely live in and are from Spain and those who speak English and most likely live in Finland but may or may not be from there, and this way see if the country of origin/residence has any influence on how the answers may vary.

The survey will have 10 questions which will be based on the concerns expressed by most articles regarding the ethics of 3D-printed organs and prosthesis and which are the following:

1. What age are you?
2. What is your nationality?
3. Would you be willing to get a 3D-printed prosthesis were you to need one?
    - Yes
    - No
4. Would you be willing to get a 3D-printed organ should you need one?
    - Yes
    - No
5. Do you believe the use of 3D-printed organs and prosthesis should be used to develop human capacities beyond what is normal for human beings? For example, changing all the bones in our bodies with 3D-printed ones, more flexible and less likely to break.
    - Yes
    - No
6. In the case of the military, do you believe their body parts should be changed to 3D-printed ones for them to extent their endurance and resistance to harm between other things?
    - Yes
    - No
7. Does the idea of people having body parts (whether they are organs or prosthesis) produced in a 3D-printer bother you?
    - Yes
    - No
8. Do you believe that, if 3D-printed organs and prosthesis become a reality, they should be available to everyone or only to those who can pay them?

    - To everyone
    - Only to those who can pay them
9. From 1 to 10, how safe would you feel with a 3D-printed organ or a 3D-printed prosthesis?
10. From 1 to 10, how safe would you feel with an organ from a donor or with a normally produced prosthesis?

The same questions, but in Spanish can be found in the appendix.

Both versions of the survey were published in Google Forms, which is a tool by Google that allows people to create and analyse surveys for free in any language. In addition to that, the answers are received immediately and can be easily sent by email to your contacts. Initially, the program Limesurvey, acquired by Arcada, was going to be the tool used to distribute the surveys, however, the language settings do not support Spanish, which is why other options were considered.

In total, 190 answers were received.

5. Results

Due to the answers to the first and second question, it was discovered that those answering the survey were between **14 and 64 years of age** and were mostly of **Spanish nationality**. A circular graph showing the differences in nationalities can be found in Figure 39.

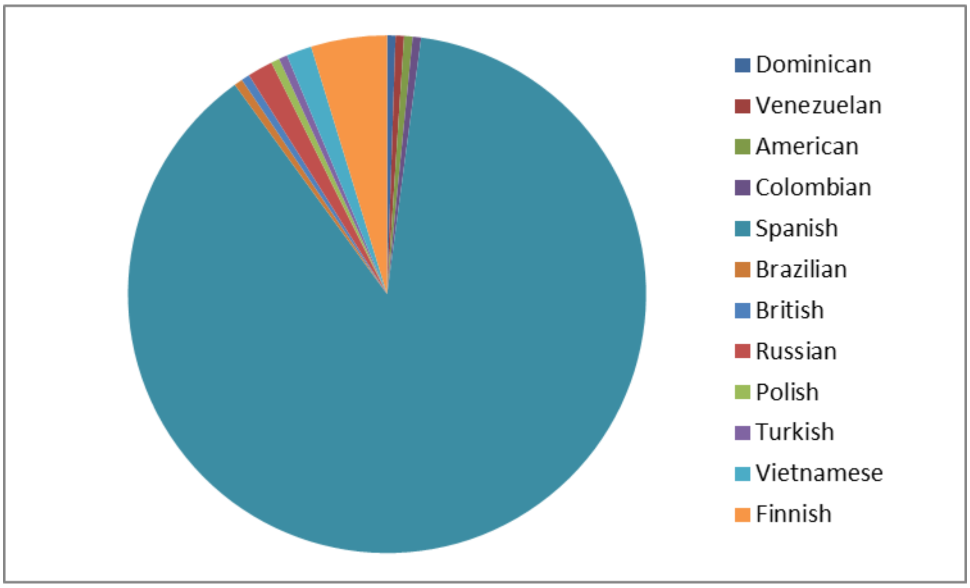

Figure 39: Differences in nationalities of the people interviewed. Spanish is the predominant one, followed by Finnish and then Russian and Vietnamese.

The third question asked whether or not the person answering it would be willing to get a 3D printed prosthesis if they needed one. The majority of them (186 people) said yes, with the negative answers (4) being significantly lower as illustrates Figure 40.

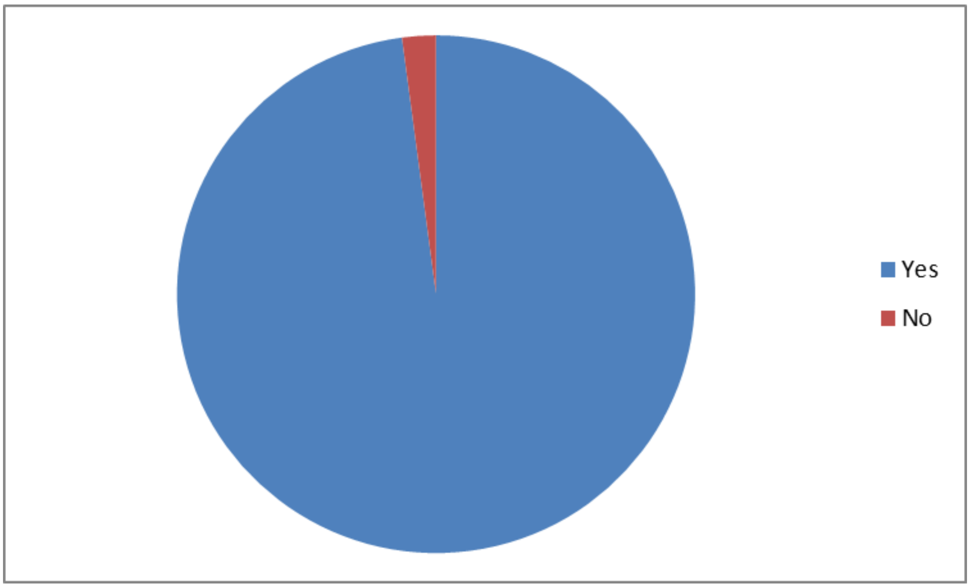

Figure 40: Comparison in answers to question number 3.

Question number 4 was basically the same as number 3 but in this case, they were asked if they were willing to get a 3D-printed organ, not prosthesis. While the answers remained mostly positive (171), the number of people saying no increased (19).

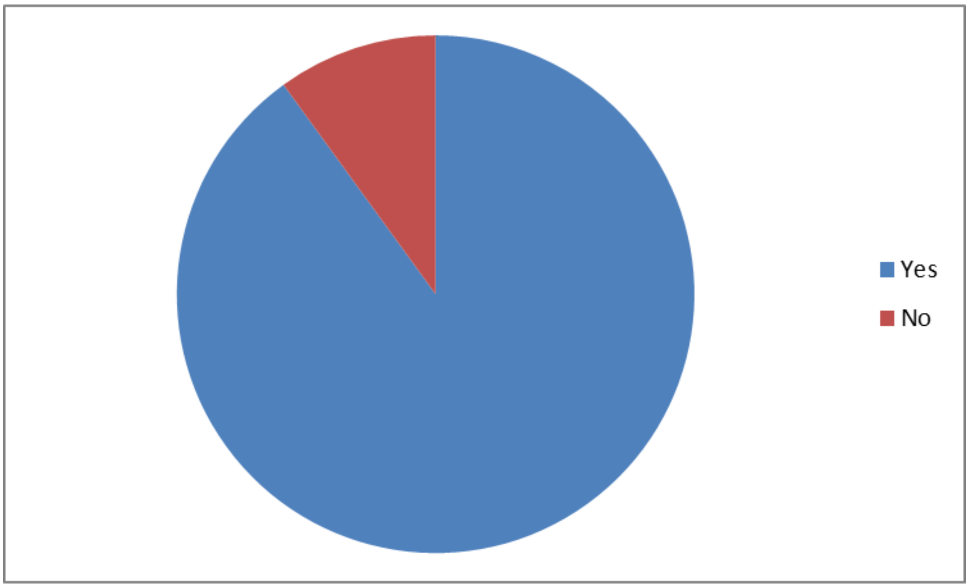

Figure 41: Circular graph illustrating the answers to the fourth question.

Fifth question was intended for people to reflect on what some believe to be the ultimate goal of 3D printed prosthesis and organs – develop human capacities beyond what is normal and therefore increase our lifespan and decrease the risk of breaking bones as well as organ failures, for example. They were supposed to say whether they believed this was a valid use of the 3D-printing technology or not. The results were inconclusive, with almost as many people saying “No” (94) as those saying “Yes” (96).

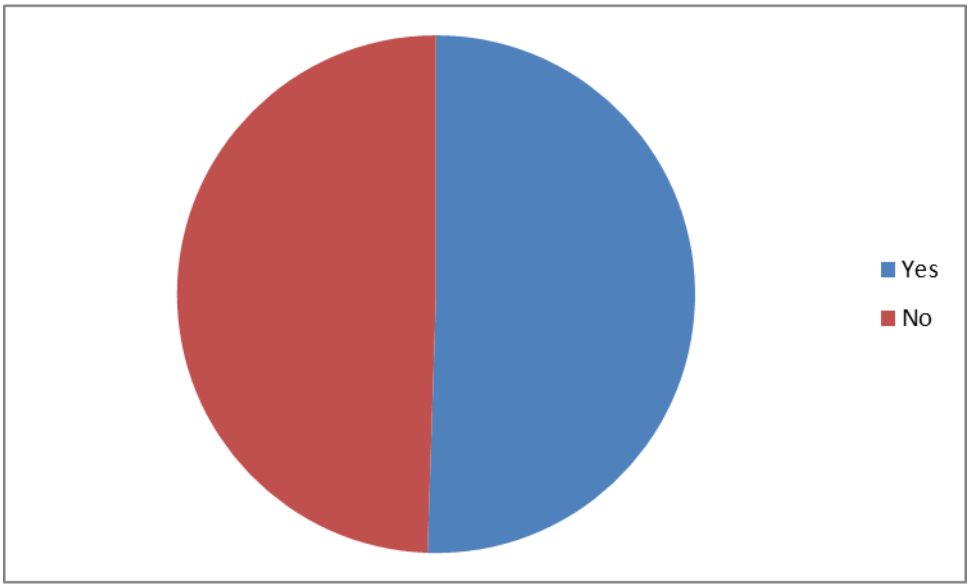

Figure 42: Circular graph showing the answers to the fifth question.

Sixth question focused on the case of the military and their need to build endurance by training and put up with a lot of pain (as it is a dangerous job where they might get shot, break some bones, get burnt… etc.) between other things. It basically asked people whether they would agree to enhancing human capacities only in that case and for the purpose of easing that job. The number of people giving a negative answer (146) was much larger than those giving a positive one (44).

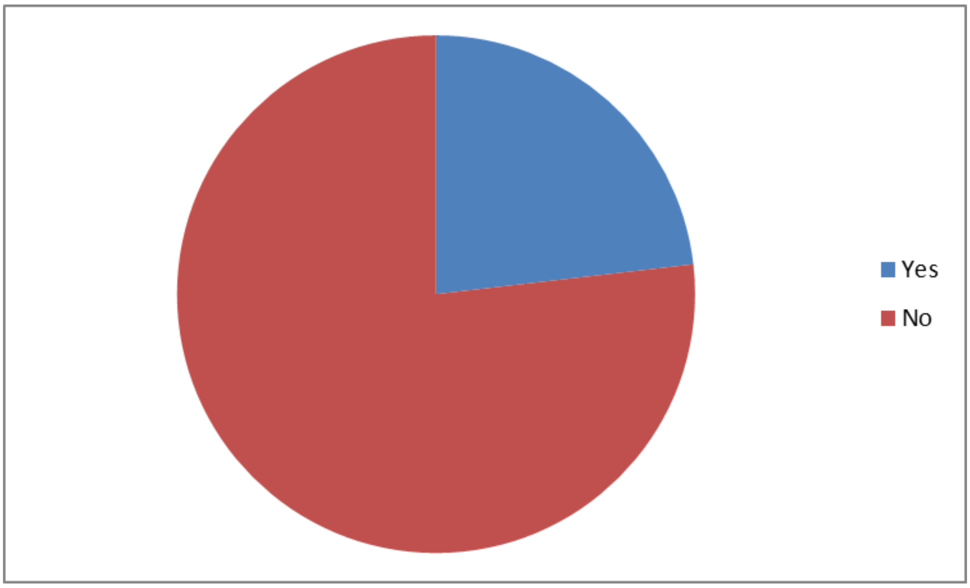

Figure 43: Circular graph showing how people answered the sixth question.

In question number 7, people were asked if they were bothered or uncomfortable by the idea of someone having 3D-printed body parts (organ or prosthesis). The answers were mostly negative (174) but a small number of people said yes (16).

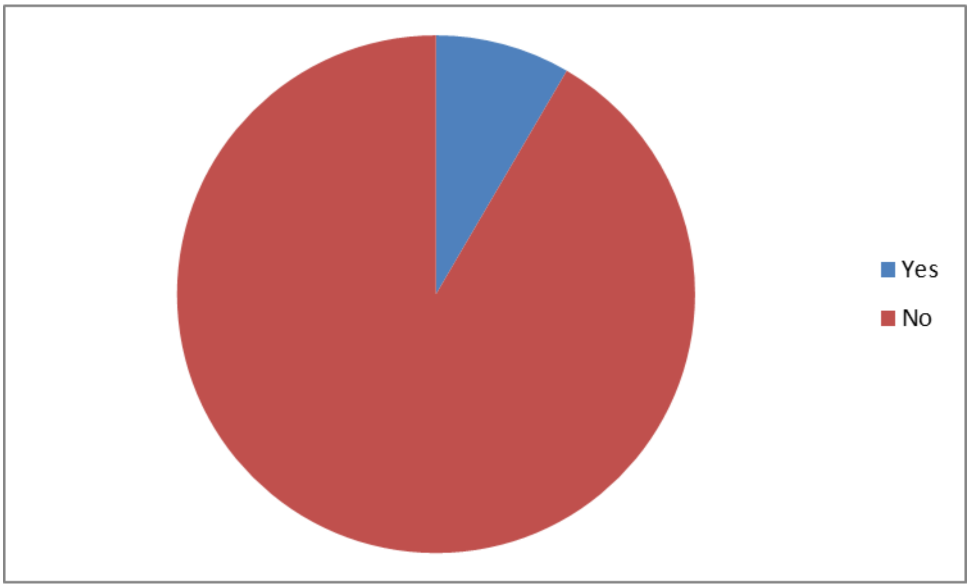

Figure 44: Answers to the seventh question.

Question 8 focused on one of the biggest economic problems of 3D-printed organs and prostheses – whether they should be available for everybody or only for those who can pay their price, as it could be assumed that, if they were to become a reality, there would be a high demand of them which would massively increase their price. Most of the people (185) agreed they should be available for everyone, with only 5 people choosing the opposite option.

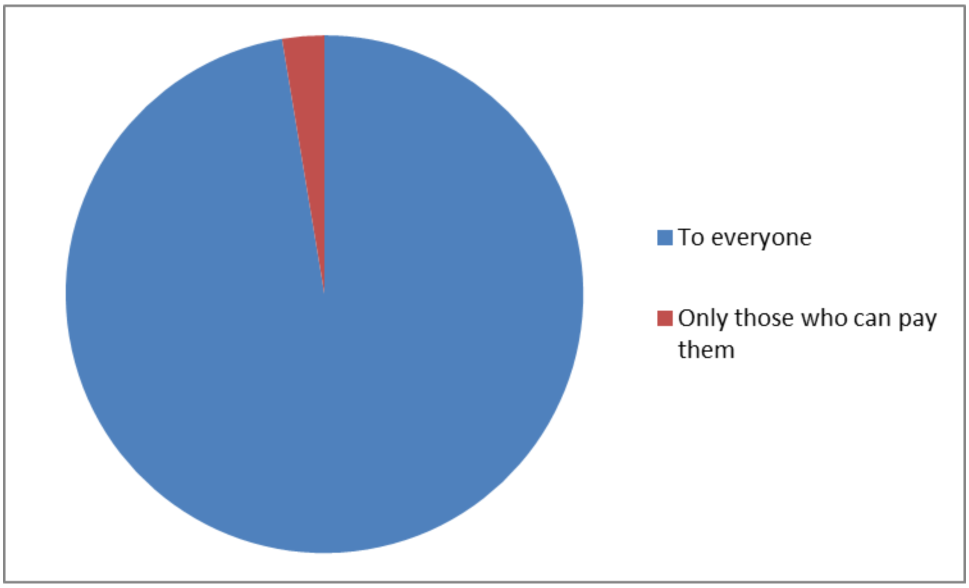

Figure 45: Graph showing a comparison between the answers to question 8 of the people interviewed.

Questions number 9 and number 10 were hoping to show if people are ready for 3D-printed organs and prostheses by assessing how safe would they feel with them and how safe would they feel with an organ from a donor and a normally produced prosthesis.

The ninth question asked how safe would they feel with 3D-printed organs and prostheses, requesting those interviewed to give a number from 1 to 10, 1 being not safe at all and 10 being very safe. 185 people gave straightforward answers to the question, but 5 people decided to specify and add the following comments: one just said they would feel "good" with a 3D-printed organ or prosthesis, another specified that he would need to talk to a doctor beforehand so that he would guarantee or not whether it would work, other said it would "depend", and two other people indicated that if it works, both of them would say 10.

Out of the 185 people who gave straightforward answers, 8 was the most popular one, with 47 people choosing it. Afterwards, 10 (33 people voted for this option) and 7 (30). The least voted options were 1 (2 people), 2 (2) and 4 (3).

The tenth question asked how safe would they feel with an organ with a donor or a prosthesis produced normally, without involving a 3D printer, again requesting those interviewed to give a number from 1 to 10, 10 being the safest. This time, 188 people gave straightforward answers, with 2 of them adding the following comments: one said that they would not know how safe they would feel, but that they would undoubtedly be “thankful” and other that they would feel “good”.

Of those who answered the question with figures, curiously number 8 was again here the favoured. However, the number of people choosing it increased (63). It was followed by 7 (32) and 10 (30). The least chosen options were 3 (1 person), 0 (3) and 4 (3).

6. Discussion

6.1 Design and simulation

Both simulations done in SolidWorks show the prosthesis having an extensive deformation on an extruded cut of 1 mm produced on what is supposed to be the palm of the hand. However, while doing the simulation, this same part could not be selected as fixed geometry (when it was done the simulation would not run), which is what the writer believes to be the main reason for this failure.

There is, notwithstanding, many reasons why an error of this type may occur: load direction or amplitude being wrong, model being either under or over restrained, parts not contacting as one once intended, parts being completely bonded when they should slide over one another, the load should have been applied to each entity instead of a being a total load, the scale of the deformation not being 1:1…

The justification for wanting to set the extruded cut as fixed geometry is because a prosthesis made out of PLA would not rotate or suffer any kind of displacement if it cannot withhold the weight of whatever it is the person wants to hold.

Therefore, it is thought that the simulation was not an accurate representation of how the arm prosthesis would behave when subjected to a load, but to test this hypothesis it would have to be printed in real-life size, built and made to hold something that weighed 100 grams and 1 kg.

In theory, the prosthetic arm should move if the changes previously discussed while explaining the procedure are applied to it. Making the forearm and hand hollow, making holes in each part of the fingers and making a string or thread pass through those holes and be pulled by some sort of electric mechanism placed inside of the forearm should allow it to move whenever the user wishes, supposing the mechanism could be activated by for example, pressing a button with the other hand.

If the arm was ever going to be printed in its original size, whether it moves or not could be tested and any problems that may arise could be solved by changing the design. Basically, what would be done is a process of trial and error. The designer would try different things, see if they work and if the case is that they do not, make whatever changes are necessary. It would also be crucially important to check in with the user of the prosthetic arm as they are the ones who will be using it full time – is it comfortable? Can they lift something lightweight? Would they want it personalized (different colour, maybe something engraved on it…)?

Regarding the scanning there are some obvious problems. First of all, taking pictures of someone’s own arm from many different angles directly is difficult and usually needs another person to get involved. This could be partially solved by creating a mould, however, and making a new arm exactly like the original. The arm in this case would have to be mirrored or else the person who uses the prosthesis would end up with two right arms or two left arms, something not practical. What happened while cleaning the scan in MeshMixer about some of the fingers not having their borders completely delimited and therefore chunks of them disappearing when cleaning the model leads the writer to believe that creating a mould would be the best option if this was the preferred approach of the person requesting the prosthesis. While the design could be edited in SolidWorks, replicating the shape of the fingers, which is non-geometrical, to fill in the voids would be extremely hard – even not possible.

On the matter of the design file being just one part, there are two solutions available for this: each part of the finger being scanned separately and then joined by creating artificial joints that allow the movement of the prosthetic fingers (and possibly the wrist if desired) using SolidWorks or some other program or scanning it all at once, then cutting the model in different parts and again, create artificial joints that permit it to move. These artificial joints should also be printed in a softer material that allows them to bend while not losing its original shape. This could theoretically be done – and would have been done had the bottom of the scanned hand been flat. Another point to take into account is the that the first app that was tried would let the user turn their scans into an .obj file or a .stl file, but not for free, which leads to the question: is scanning more economically viable?

The answer is, it depends. The scanned nail polish bottle did not look too bad, but it was also not good enough, especially if it is taken into account that what is really being considered in this thesis is the production of prosthetic arms that a person is going to wear every day of their life. The hand done with Trnio did look very well, but there was the problem of the non-delimited edges. And the scan done with ReCap Photo did not even look like the object at all, though it is believed that was the user’s fault. It is important to keep in mind however that the user did not have a lot of experience with scanning apps, that most likely the design could have been improved in Meshmixer, obtaining a much cleaner result and also, that these scanning apps that did produce scans were free or almost and most likely, an app or scanner that has a higher cost would produce better results (and so would ReCap Photo if used a different approach). So if an enterprise producing prosthetic arms could get the cost back of whatever scanner they use, it could be more economically viable than using modelling software as these tend to have a very high cost.

Either way, the end result would be similar to the one achieved by doing the design in SolidWorks from scratch – many different parts that have to be assembled. Whether this is more time effective or not, it would be hard to say, as it not only depends on the procedure but also on the experience of the designer and how well can they manipulate already existing files. What is true is that the end result might be less robotic-looking as it would be the carbon copy of a real arm so it could be more aesthetically pleasing if done well.

6.2 Survey

It could not be said that the results of the survey were unexpected as they more or less showed the same results that the writer was expecting.

Most people seem to be ready to welcome the idea of 3D-printed organs and prostheses with open arms – especially young people, as it was usually older people who said that they would not get a 3D-printed organ or prosthesis (although most of them seem a lot more positively inclined to the idea of getting a prosthesis) and that they would be bothered by people having them. This seems normal as it is usually older people who have more difficulty adapting to and accepting new scientific breakthroughs that may make them question aspects of life they thought they had completely figured out.

There was also a much divided response to the question of using this technology to enhance human abilities, but it was surprising to see that the same did not happen for the question involving enhancing the military's human abilities, with most of the answers for this one being negative. A reason why this may have happened is because in this question there are many other things to consider – the stance of those answering on supporting or not the military (which may vary depending on the country they come from or they live in), experiences they may have gone through involving said group (civil wars or just about any kind of political conflict they may have seen themselves involved in) and if they support this use of 3D-printers in general.

Obviously, economically speaking, most people would like 3D-printed organs and prosthesis to be available to everybody but whether this is realistic or not is yet to be discovered. It is widely assumed that if this was to become a reality the demand for them would be massive which could lead to a very high price if the production of organs and prostheses by this method is not fast and cheap enough.

A great number of people think they would feel equally safe with an organ from a donor than with a 3D-printed organ and with a normally produced prosthesis than with a 3D-printed one, considering their doctor would give their approval. What could be derived from these two questions is that people in general are not against the idea of themselves trying this new technology if those responsible for taking care of their health are not against it. However, more people would feel safer with using the methods already in existence, which is obvious as human beings in general tend to fear the unknown and do not like being experiment with – hence why usually these things are first tried in animals.

6.3 Improvements

Regarding the design, the first improvements coming to mind are the changes that need to be done to make the prosthetic arm move. What it needs would be: the forearm and hand hollow, holes in each part of the fingers and a string or thread that passes through those holes and is pulled by some sort of electric mechanism placed inside of the forearm.

In the case these changes are done, the prosthesis is printed, and it still does not move, the reason for this would have to be found (best guess would be the soft elements that connect each part of the finger are either too soft that the fingers are always bending or too hard that they cannot bend at all) and a solution for it given (changes of material, changes in design).

The rest of the things that may be changed for the better would have to be talked about with the person using the prosthesis. The colour, different measurements to make the arm more comfortable, a more flexible material or basically anything that the user recommends would have to be implemented even if aesthetically it is not as intended as, after all, it is them who will be using this every day of their life.

The number of people answering the survey was higher than expected and there was variety when it came to the age of those interviewed so there are no possible improvements in those areas. However, the number of people who answered the survey in Spanish is a lot higher than those answering it in English. This does not mean that everybody who answered the survey in Spanish is from Spain, but almost all of them were. Having more people from different nationalities would have been interesting and would have given the possibility of seeing how the answers differed from one country to another. Comparisons in age could be made, however.

Another improvement is that, next time, all the options of the survey would have to be marked as compulsory, as some of them were submitted missing one or two answers, which meant that they had to be disregarded as vital information was missing.

Something to consider is to have those interviewed mention their area of work, as it could be interesting to see if a person working in the medical field has the same views as a person who works on a constructions site and does not know so much about the topic, for example.

7. Conclusion

To conclude, the objectives for the creation of the arm were theoretically fulfilled. It should fit perfectly a 20-something year old woman of the same height and weight than the writer as it was created using her measurements but that would have to be proven by printing the prosthesis and trying it on. Any changes on measurements could be performed quickly and easily though. It should move and lift some weight if the necessary changes are performed. And it should be lightweight due to the material used and economically viable for those who cannot afford a very expensive one.

Doing the prosthetic arm in SolidWorks from scratch is, in the writer's opinion, the most time effective option as it is what they have more expertise in and by no means should this be the case for everyone. However, if for whatever reason the person who will use the arm wants the prosthesis to resemble a real, human arm, scanning would be the best option. Also if they just wanted it for aesthetic purposes – for a special occasion such as attending a party, a photoshoot… and did not need the fingers to perform any movement at all, then it basically could be done within hours. Economically speaking it would depend on the enterprise producing the prostheses and whether they could get back or not the cost of the scanner or the modelling software they used. In the case of the writer, as SolidWorks is provided for free to her by the university, creating the design from scratch in there is obviously better.

The survey proved that society is mentally ready for 3D-printed prosthesis and organs, at least the younger people, and even some older people if doctors and specialists approve of them and guarantee that they have a high probability of working. Prostheses are regarded as being safer and less invasive than organs, and people would have less doubts getting one. What they may not be ready for is to pay exorbitant prices if this new technology were to reach them. Nonetheless, these are just conjectures.

It is important to mention that society's behaviour may change if 3D-printed organs and prosthesis were to be made a reality and there was, for example, an accident with one of them in which a person passed away. All in all, nothing is definite and we, as society, must wait and see how things develop. The future, which may be closer than we think, may prove this thesis to be wrong or right.

8. References

1. Flynt, J. 2017. A Detailed History of 3D Printing. [online] Available from: http://3dinsider.com/3d-printing-history/ Last accessed: 04/06/2018
2. Lonjon, C. 2017. The history of 3d printer: from rapid prototyping to additive fabrication. [online] Available from: https://www.sculpteo.com/blog/2017/03/01/whos-behind-the-three-main-3d-printing-technologies/ Last accessed: 04/06/2018
3. Mendoza, HR. 2015. Alain Le Méhauté, The Man Who Submitted Patent for SLA 3D Printing Before Chuck Hull. [online] Available from: https://3dprint.com/65466/reflections-alain-le-mehaute/ Last accessed: 04/06/2018
4. https://www.thingiverse.com/
5. 3D Printing From Scratch. 2015. Types of 3D printers or 3D printing technologies overview. [online] Available from: http://3dprintingfromscratch.com/common/types-of-3d-printers-or-3d-printing-technologies-overview/ Last accessed: 04/06/2018
6. 3D Insider. 2017. The 9 Different Types of 3D Printer. [online] Available from: http://3dinsider.com/3d-printer-types/#fdm Last accessed: 04/06/2018
7. Lipson, H, & Kurman, M 2010, Fabricated : The New World of 3D Printing, John Wiley & Sons, Incorporated, Somerset. Available from: ProQuest Ebook Central.
8. 3D Printing for Beginners. 2013. What Material Should I Use for 3D Printing? [online] Available from: http://3dprintingforbeginners.com/filamentprimer/ Last accessed: 04/06/2018
9. Palermo, E. 2013. What is stereolithography? [online] Available from: https://www.livescience.com/38190-stereolithography.html Last accessed: 04/06/2018
10. Horne, R, & Hausman, KK 2017, 3D Printing for Dummies, John Wiley & Sons, Incorporated, Newark. Available from: ProQuest Ebook Central.
11. Chowdhry, A. 2013. What Can 3D Printing Do? Here Are 6 Creative Examples. [online] Available from: https://www.forbes.com/sites/amitchowdhry/2013/10/08/what-can-3d-printing-do-here-are-6-creative-examples/#699301385491 Last accessed: 04/06/2018
12. Kor Ecologic. 2013. Urbee 2. [online] Available from: https://korecologic.com/about/urbee_2/ Last accessed: 04/06/2018
13. Sculpteo. Mastering Aronautics and Aerospace prototyping. [online] Available from: https://www.sculpteo.com/en/applications/aeronautics-and-aerospace/ Last accessed: 04/06/2018
14. Armstrong, K. 2016. 3D Printed Dress Debuts at New York Fashion Week. [online] Available from: https://3dprintingindustry.com/news/3d-printed-dress-debuts-new-york-fashion-week-95736/ Last accessed: 04/06/2018
15. Schubert, C; van Lageveld MC & Donoso LA. 2014. *Innovations in 3D printing: a 3D overview from optics to organs.* [online] Available from: https://www.ncbi.nlm.nih.gov/pubmed/24288392/ Last accessed: 04/06/2018

16. Banks J. *Adding value in additive manufacturing: Researchers in the United Kingdom and Europe look to 3D printing for customization*. 2013.
17. Sculpteo. Use 3D Printing to Create Medical Devices, Dental and Prosthesis. [online] Available from: https://www.sculpteo.com/en/applications/medical/ Last accessed: 04/06/2018
18. García RR. 2016. Un niño de Arteixo recibe una prótesis de brazo hecha con una impresora 3D. [online] Available from: https://www.lavozdegalicia.es/noticia/sociedad/2016/02/09/nino-arteixo-recibe-protesis-brazo-hecha-impresora-3d/0003_201602G9P24991.htm Last accessed: 04/06/2018
19. Enabling The Future. About us. [online] Available from: http://enablingthefuture.org/about/ Last accessed: 04/06/2018
20. Birrell, I. 2017. 3D printed prosthetic limbs: the next revolution in medicine. [online] Available from: https://www.theguardian.com/technology/2017/feb/19/3d-printed-prosthetic-limbs-revolution-in-medicine Last accessed: 04/06/2018
21. Sullivan, G. 2014. Man prefers $50 3-D printed hand to $42,000 prosthetic. [online] Available from: https://www.washingtonpost.com/news/morning-mix/wp/2014/04/23/man-prefers-50-3d-printed-hand-to-42000-prosthetic/?utm_term=.68d2f7e4b8a0 Last accessed: 04/06/2018
22. 3D Universe. 2014. A $50 3D-Printed Prosthesis Compared to a $42,000 Myoelectric Prosthesis. [video] Available from: https://www.youtube.com/watch?v=CHPuMCshkLU&src_vid=BkK06113IGE&feature=iv&annotation_id=annotation_3579992065 Last accessed: 04/06/2018
23. Lee Ventola, C. *Medical Applications for 3D Printing: Current and Projected Uses*. 2014
24. Lewis, T. 2017. Could 3D printing solve the organ transplant shortage? [online] Available from: https://www.theguardian.com/technology/2017/jul/30/will-3d-printing-solve-the-organ-transplant-shortage Last accessed: 04/06/2018
25. MedlinePlus. Transplant rejection. [online] Available from: https://medlineplus.gov/ency/article/000815.htm Last accessed: 04/06/2018
26. Scott, C. 2016. Wake Forest Researchers Successfully Implant Living, Functional 3D Printed Human Tissue Into Animals. [online] Available from: https://3dprint.com/119885/wake-forest-3d-printed-tissue/ Last accessed: 04/06/2018
27. BBC Mundo. 2016. Anthony Atala, el científico peruano que busca un lugar en la historia de la medicina con una impresora. [online] Available from: http://www.bbc.com/mundo/noticias/2016/03/160315_atala_impresora_organos_am Last accessed: 04/06/2018
28. Fox, M. 2016. Wake Forest University Scientists Print Living Body Parts. [online] Available from: https://www.nbcnews.com/health/health-news/wake-forest-university-scientists-print-living-body-parts-n518981 Last accessed: 04/06/2018

29. Cellink. Our Inks. [online] Available from: https://cellink.com/bioink/ Last accessed: 04/06/2018
30. Murphy, Dan. 2017. This robot is learning how to print a human organ. [online] Available from: https://www.cnbc.com/2017/06/23/advanced-solutions-develops-first-3d-human-tissue-printer-that-operates-on-six-axis-robot.html Last accessed: 04/06/2018
31. Salleh, A. 2017. Scientists create 3D-printed brain-like tissue from stem cells. [online] Available from: http://www.abc.net.au/news/science/2017-07-26/scientists-create-3d-printed-brain-like-tissue-from-stem-cells/8740794 Last accessed: 04/06/2018
32. Rouse, M. 2009. Rendering. [online] Available from: http://whatis.techtarget.com/definition/rendering Last accessed: 04/06/2018
33. SolidWorks. Información de la empresa. [online] Available from: http://www.solidworks.es/sw/183_ESN_HTML.htm Last accessed: 04/06/2018
34. Sculpteo. Prepare your model for 3D printing with SolidWorks. [online] Available from: https://www.sculpteo.com/es/tutoriales/preparar-su-modelo-para-la-impresion-3d-con-solidworks/ Last accessed: 04/06/2018
35. Computer Aided Design Guide. 2016. What Is SolidWorks Used For? [online] Available from: http://www.computeraideddesignguide.com/what-is-solidworks-used-for/ Last accessed: 04/06/2018
36. SolidWorks. 3D Cad. [online] Available from: http://www.solidworks.com/sw/products/3d-cad/print-directly-to-3d-printers-3mf-and-amf-formats.htm Last accessed: 04/06/2018
37. Formizable. 2018. Aprende Meshmixer para imprimir en 3D – nivel principiantes. [online] Available from: https://formizable.com/aprende-meshmixer-para-imprimir-en-3d-nivel-principiantes/ Last accessed: 18/09/2018
38. The Open University. 6 Methods of data collection and analysis.
39. Atlas, Qualitative Data Analysis. Qualitative and Quantitative Research: Comparison of Qualitative and Quantitative Research. [online] Available from: http://atlasti.com/quantitative-vs-qualitative-research/ Last accessed: 04/06/2018
40. Qualitative vs Quantitative analysis. [online] Available from: http://www2.sal.tohoku.ac.jp/ling/corpus3/3qual.htm Last accessed: 04/06/2018
41. Aponte, K; Arevalo, E; Cordero, D et al. Prótesis de brazo mecánica. [online] Available from: https://es.slideshare.net/washo144/prtesis-de-brazo-mecnica Last accessed: 04/06/2018
42. DT Works, 2017. HOW TO DESIGN ARTICULATED WOODEN HAND (4/4). [video] Available from: https://www.youtube.com/watch?v=yOEtT6oqwCk Last accessed 26/6/2018.
43. Enabling the Future. Build a hand. [online] Available from: http://enablingthefuture.org/upper-limb-prosthetics/ Last accessed 27/06/2018.
44. Filabot, 2015. The Misleading Biodegradability of PLA. [online] Available from: https://www.filabot.com/blogs/news/57233604-the-misleading-biodegradability-of-pla Last accessed 11/07/2018.

45. Wainwright, O. 2013. The Filabot will revolutionise the home 3D-printing market. [online] Available from: https://www.theguardian.com/artanddesign/architecture-design-blog/2013/jan/15/filabot-home-3d-printing-recycle Last accessed: 15/10/2018
46. Lievendag, N. 2018. Trnio Iphone Photogrammetry App Review. [online] Available from: https://3dscanexpert.com/trnio-iphone-photogrammetry-app-review/ Last accessed: 15/10/2018.
47. Cornwall Museums Partnertship. Weekly Tech Review – Week 5 Sketchfab – publishing 3D scans. [online] Available from: https://www.cornwallmuseumspartnership.org.uk/weekly-tech-review-week-5-sketchfab-publishing-3d-scans/ Last accessed: 20/01/2019
48. Trnio. Tutorial: How To Get Started & In-Depth Tutorial. [online] Available from: http://www.trnio.com/tutorial/ Last accessed: 20/01/2019

8.1 Figures

Figure 1: Kor Ecologic. 2013. Urbee 2. [online] Available from: https://korecologic.com/about/urbee_2/ Last accessed: 04/06/2018

Figure 2: Ponyboy Magazine. threeASFOUR, spring 2017. Photography by Alexander Thompson. Available from: https://ponyboymagazine.com/threeasfour-spring-2017/ Last accessed: 09/12//2018

Figure 3: Sharma Rakesh. The 3D printing revolution you have not heard about. June 8, 2013. Available from: https://www.forbes.com/sites/rakeshsharma/2013/07/08/the-3d-printing-revolution-you-have-not-heard-about/#4ecc995f1a6b Last accessed: 09/12//2018

Figure 4: Hodgkins, Kelly. College student 3D prints his own Invisalign braces, which work amazingly well. March, 2016. Available from: https://www.digitaltrends.com/cool-tech/3d-printed-invisalign-braces/ Last accessed: 09/12//2018

Figure 5: García RR. 2016. Un niño de Arteixo recibe una prótesis de brazo hecha con una impresora 3D. [online] Available from: https://www.lavozdegalicia.es/noticia/sociedad/2016/02/09/nino-arteixo-recibe-protesis-brazo-hecha-impresora-3d/0003_201602G9P24991.htm Last accessed: 04/06/2018

Figure 6: Atala, Anthony. Printing a Human Kidney. TED2011. Available from: https://www.ted.com/talks/anthony_atala_printing_a_human_kidney Last accessed: 09/12//2018

Figure 7: Three parts theory. As Far As The Eye Can See: How Skyrim Distorts Spatial Relationships. Available from: https://threepartstheory.wordpress.com/2011/11/23/as-far-as-the-eye-can-see-how-skyrim-distorts-spatial-relationships/ Last accessed: 09/12//2018

9. Appendix

1. ¿Cuál es tu edad?
2. ¿Cuál es tu nacionalidad?
3. ¿Estarías dispuesto a llevar una prótesis creada con una impresora 3D si la necesitases?
    - Sí
    - No
4. ¿Estarías dispuesto a implantarte un órgano creado con una impresora 3D si lo necesitases?
    - Sí
    - No
5. ¿Crees que el uso de órganos y prótesis hechos con impresora 3D deberían usarse para desarrollar las capacidades humanas más allá de lo normal para los seres humanos? Por ejemplo, cambiando los huesos de nuestro cuerpo por unos hechos con impresora 3D, que sean más flexibles y se rompan menos.
    - Sí
    - No
6. En el caso de los militares, ¿crees que partes de su cuerpo deberían cambiarse por aquellas hechas con impresora 3D para extender su resistencia y aguante al dolor, entre otras cosas?
    - Sí
    - No
7. ¿La idea de que otra persona tenga partes de su cuerpo (ya sean órganos o prótesis) producidas en una impresora 3D te hace sentir incómodo?
    - Sí
    - No
8. Si los órganos y prótesis producidos en impresora 3D se convirtieran en una realidad, ¿deberían estar disponibles para todos o solamente para aquellos que puedan permitírselos?
    - Todos
    - Solo aquellos que puedan permitírselos
9. Del 1 al 10, ¿cómo de seguro te sentirías con una prótesis u órgano creado en una impresora 3D?
10. Del 1 al 10, ¿cómo de seguro te sentirías con un órgano recibido de un donante habitual o una prótesis producida normalmente?