Tampere University of Applied Sciences

Biomimicry in Mechanical Prosthesis Design and 3D-printing

Clemens Ebeling

BACHELOR'S THESIS
July, 2020

Mechanical Engineering

ABSTRACT

Tampereen ammattikorkeakoulu
Tampere University of Applied Sciences
Production Engineering

EBELING, CLEMENS:
Biomimicry in Mechanical Prosthesis Design and 3D printing

Bachelor's thesis 42 pages
July, 2020

The implementation of biomimicry in the design process of prostheses provides new ideas and approaches for their development and increases the applied possibilities of this technology. In combination with new production methods such as 3D printing, a few of these new ideas can be realized easier compared to traditional manufacturing processes. The objective of this work was to find ways to implement biomimicry in the design process of prostheses, and methods to optimize them applying this technique. According to literature dealing with the subjects of biomimicry, 3D printing and prosthetic devices, there is a relationship between the design process of nature and the production of these devices using additive manufacturing.

The topology optimization is one nature-inspired process where the geometry of a prosthesis can be optimized using a complex algorithm. Using the Altair Inspire software the mass of a device can be reduced while its stiffness is maximized. The simulated results often display a complex geometrical structure which is difficult to produce with common manufacturing methods. These results can also be further modified to achieve a more sophisticated part. Because of the flexibility of 3D printing, it is possible to construct these biomimicry structures even when they consist of hollow or slender structures.

Key words: prostheses, 3d-printing, biomimicry, topology optimization

CONTENTS

ABBREVIATIONS AND TERMS

ABS	acrylonitrile butadiene styrene
CAD	computer-aided design
CAM	computer-aided manufacturing
CNC	computerized numerical control
E	elastic modulus
FDM	fused deposition modelling
FEA	finite element analysis
FG	degrees of freedom
Kg	kilogram
mm	millimetre
mm^2	square millimetre
MPa	Mega Pascal
N	newton
P	penalization factor
PLA	polylactic acid
SIMP	solid isotropic material with penalization
SLA	stereolithography apparatus
SLS	selective laser sintering
ρ	density
3D	three dimensional

1 INTRODUCTION

In the last few years, the development of prostheses has improved greatly. The general concept of replacing a lost extremity has been a difficult task ever since and the variety of problems are solved in many ways. The technological level of the different prostheses diverges from simple rigid constructions to complex ones equipped with modern sensorics and powered by electric motors capable of performing a certain move set.

Considering all that, there is still a long way before a prosthetic device can work as a complete replacement of an extremity and the demand for them is and will be always consistent. Questions about the access to affordable prostheses that offer a high quality and useful assistance display the focus points in the development and the production of these.

By using the 3D-printing technique for producing prostheses it is possible to increase the accessibility for the individual, while at the same time the cost can be reduced. There is a wide range of 3D-printable prostheses available, which an individual can print on their own and use without having the knowledge necessary to design the devices by themselves. Even though these simple constructions often lack more complex functions they enable an easily to use wide distribution.

When it comes to improvements of these it is possible to get some inspiration by nature and apply the concept of biomimicry on the construction. Here the concepts help to find solutions regarding the design and production of used materials or even to improve the structure of the components itself. Because of the different possibilities of improvement regarding the 3D-printed prostheses the topic of this research is to find helpful implementations of biomimicry into the design and production process of prostheses. Especially the optimization of a prosthetic device regarding its design is one of the main focus points.

2 Biomimicry in Engineering

This chapter shows the implementation possibilities of biomimicry in the field of engineering. Hereby, the focus is on prosthetic devices and the connections between the two topics.

2.1 General usage of biomimicry

Biomimicry engineering is nowadays an inherent part of the modern application of engineering. The basic concept of copying the nature to solve different problems has always been a significant way of implementing new ideas in design and production of materials, structures, and systems in the field of engineering. (Bhushan, 2009) (Kulkarni & Saraf, 2019)

This field, also known under the terms biomimetics, bionics or biognosis, is highly interdisciplinary. It contains the knowledge of biological structures, functions, and principles of a variety of objects in nature from a perspective of biologists, chemists, material scientists and physicists. Furthermore, the commercial interest of engineers, chemists, material scientists and others towards the design and fabrication of numerous materials and devices is part of the needed understanding. (Bhushan, 2009) (Sani, Muftah, & Siang, 2013)

Nature uses a complex combination of the surface structure and morphology as well as the chemical and physical properties to shape the characteristics of materials and surfaces. For that, it uses materials that often occur in the environment. This results in a various amount of different materials, surfaces and devices that each fulfil numerous functions that are of technical and commercial interest. “Molecular-scale devices ,superhydrophobicity, self-cleaning, drag reduction in fluid flow, energy conversion and conservation, high adhesion, reversible adhesion, aerodynamic lift, materials and fibres with high mechanical strength, biological self-assembly, antireflection, structural coloration, thermal insulation, self-healing and sensory-aid mechanisms” (Bhushan, 2009) are a few of this examples. (Bhushan, 2009)

In more detailed manner, with respect to recent innovations, technology applications for example in the field of prosthetics, artificial neural networks or genetic algorithms are becoming increasingly more important (Kulkarni & Saraf, 2019).

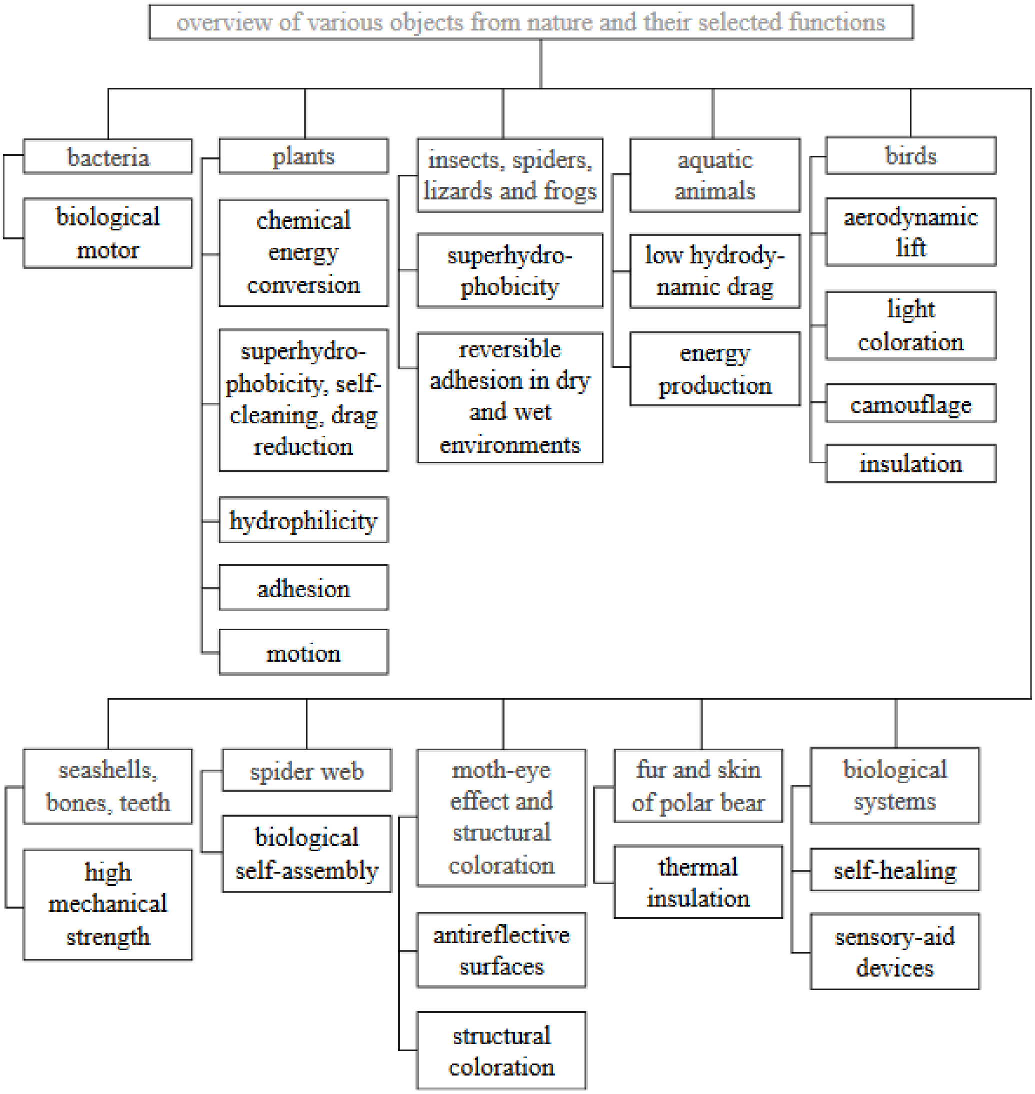

Figure 1: An overview of various objects from nature and their selected functions (Bhushan, 2009)

Figure 1 shows a variety of objects from nature and their selected functions that can be used in the field of engineering. Living and non-living nature both provide established solutions to tasks of the modern engineering. Here the challenge is in a useful implementation of the concepts from nature in a context that offer a profitable and advantageous realization of them. For this work especially the technical benefits of reducing the weight and maintaining the high mechanical strength like found in the structure of seashells, bones or teeth are of special interest. (Bhushan, 2009)

2.2 Biomimicry in prosthesis

When it comes to biomimicry the prosthesis itself is already a way of coping the nature and therefore an example of this method (Kulkarni & Saraf, 2019). Nonetheless there are other forms of Biomimicry that can influence the construction of the prosthesis. Especially when it comes to the material and the construction of it there are multiple ways to improve the prosthesis by copying the nature and take advantage of certain natural mechanisms. (Nayak & Lenka, 2018)

One of the biggest organ systems of the human body are the support and movement organs. They fulfil the primary mechanical tasks as well as the stance and movement necessities. Furthermore, they also can detect incoming forces, joint movement speeds and proprioceptive joint angles and perceive temperatures, therefore they serve as sensors of the body. The feet and especially the hands are, by using their sense of touch, highly sensitive sensory organs. Moreover, are these organs responsible to produce blood, work as storage of minerals and the protection of other inner organs. In case of sickness, injuries, malformations, or amputations of the organs the entire body suffers from limitations in all these aspects. (Wintermantel, 2009, S. 1761)

The most amputations occur at the lower and upper extremities, indispensable for the entire process of motion. (Bielmeier, 2010) For that reason, the following chapters are focused on the functionality and the challenges of replacing these.

2.2.1 Upper extremities

The shoulder, arm and the hand form a unit that allows a free movement of the hand in a room. The hand is a diverse grabbing tool that enables the development of force, the use of gestures for communication and by its sense of touch a perception of the surroundings. There is also a close connection between the hand and the brain which allows a fluent exchange of information between the two. (Wintermantel, 2009)

By using the shoulder and the arm the hand can reach every position inside of the possible radius of the extremities and in eyesight. Even spots behind the back or the backside of the head can be reached. This workspace is made possible by the ball joint connection of the shoulder and the chest. In combination with the muscles in that area a high mobility is enabled. The entire shoulder complex therefore is kitted out with seven degrees of freedom (FG) for its movement as shown in figure 2.

In the centre of the arm the elbow joint consists out of two joints where one provides the function of a hinge joint and the other is partly responsible for the turning of the lower part of the arm. For that reason, the elbow joint has two degrees of freedom. The wrist joint provides two degrees of freedom and allows precise movements that allow the hand to grab objects easily. (Wintermantel, 2009)

Figure 2 shows all the degrees of freedom in the upper extremity. The open linked chain consisting of shoulder, arm and hand enable the movement of the hand. There are 11 degrees of freedom required to position the hand and another 22 for the procedure of the grabbing motion.

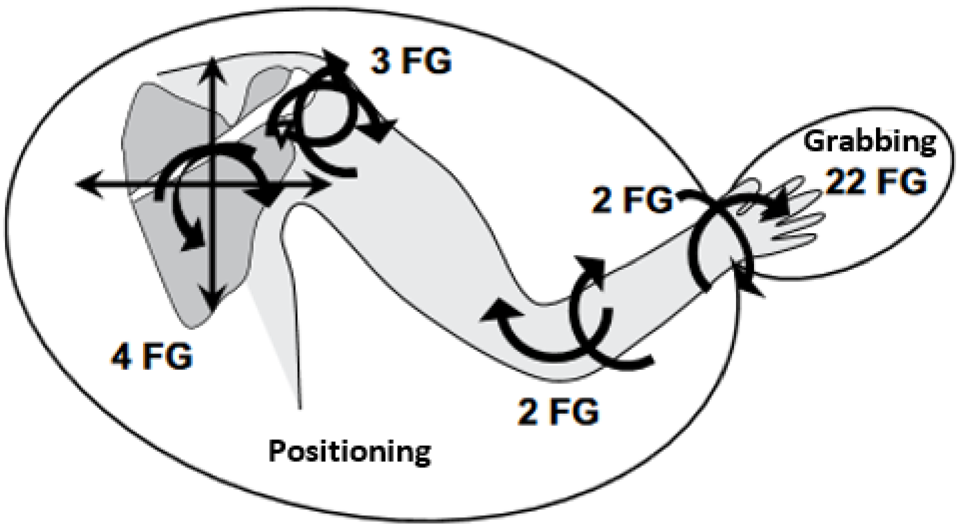

Figure 2: Degrees of freedom for the upper extremities (Wintermantel, 2009, S. 1762)[Translated]

Considering all these requirements the difficulties of a prosthesis replacement can be watched especially when it comes to the complexity of the hand itself. After the loss of a limb the precise control of this area of the body by the brain is impossible and cannot be reproduced with our current state of technology. In particular the grabbing motion of the hand is currently irreplaceable. The prosthesis needs to be controlled consciously and the user needs to see the object and the prosthesis at all time when using it. The amount of degrees of freedom that can be used is effectively reduced to two, otherwise the operation of the prosthesis becomes too complex. For that reason, the technical solution often results in claw grip function which can be handled more easily.

Due to an amputation the affected person further loses the ability to create force with the limb and to transfer the incoming forces through the structure of it. When it comes to holding, lifting, or carrying of objects the prosthesis therefore needs to withstand the occurring pull forces.

Also, the weight distribution needs to be considered to support the natural walking movements of swinging the arms next to the body and to avoid a lopsided posture.

When it comes to an amputation it is therefore important to save as much as possible of the natural state of the limb to maintain the sensitivity and bone and muscle structure. With these measures the possibility of a larger range of motion and more complex movements can be achieved, and the amputee has the chance of a more natural set of movements. (Wintermantel, 2009)

Furthermore, what kind of prosthesis is used needs to be considered. There is a great variety of different prostheses for the same body part and the different level of complexity is part of the decision for every user. (Maat, Smit, & Plettenburg, 2017)

2.2.2 Lower extremities

The posture and movement organs are well equipped for walking on a horizontal distance. During the walking, the chain of limbs of the lower extremities change in a rhythm between an open and a closed linked chain. Even though, the upper part of the body is essential for the movement the lower extremities are despite the lack of movement varieties, vital for the locomotion and posture of the body. (Wintermantel, 2009) (Bielmeier, 2010)

The basic requirement for the human mobility is the ability to stand. During the process of standing on both feet the bodyweight gets distributed equally on both legs, which means that the vertical force component in each leg is half the body-weight. The joints inside the hip, knee and foot are exposed to the ground reaction forces in a vertical orientation, shown in figure 3 in the sagittal view. In the frontal view the ground reaction forces act slightly at an angle. (Wintermantel, 2009)

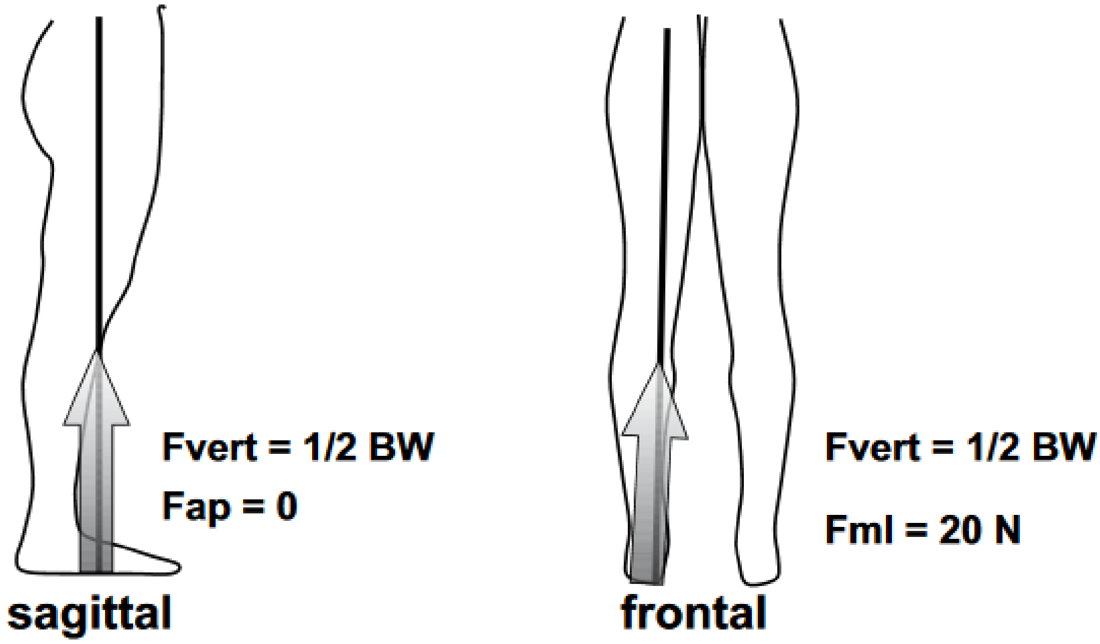

Figure 3: Reaction forces while standing (Wintermantel, 2009)

When it comes to walking the entire process, called the walking cycle, is divided into two parts the standing phase and the swinging phase. There is a complex combination of movement between the individual joints that transfer into fluid transition between the two phases.

While standing the ground reaction forces create an angular momentum outside of the joints shown in figure 4 the muscle structure in the leg guarantees the stability and functionality of the joints and creates a counter angular momentum. The collaboration between that momentum is the basis for the entire motion process required for walking.

The knee joint is especially important when it comes to movements of the leg like siting, standing up, taking stairs or just normal walking. As soon as a person starts walking the joint inside of the knee is part of the movement and is exposed to different kinds of forces and at some point, during the walking cycle, the knee is almost carrying the entire bodyweight. When it comes to other movements than walking the knee is under different types of loads and has different types of forces working on it.

All together the lower extremities have six degrees of freedom. The hip has three, the knee one and the upper and lower ankle each have one. The functionality and the stability of the lower extremities during the walking process as shown in figure 4 result out of the combination of muscles and joints that react to the ground reaction forces and. (Wintermantel, 2009),(Bielmeier, 2010)

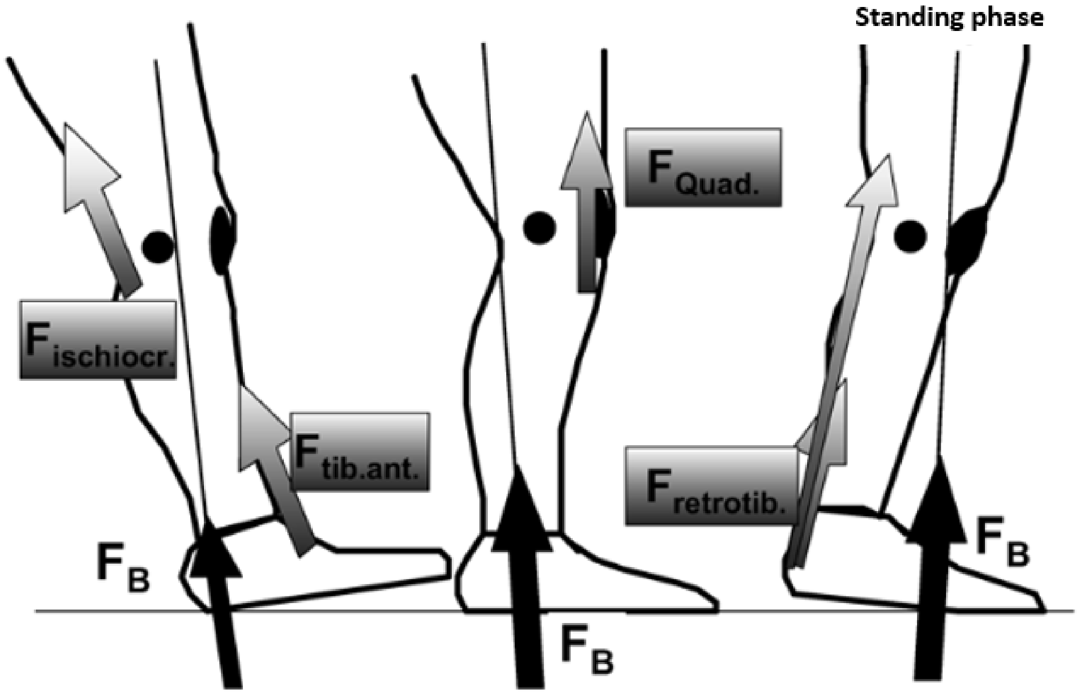

Figure 4: Functionality and stability of the lower extremities while walking (Wintermantel, 2009)[Translated]

For the biomechanical requirements it is therefore important to restore the possibility to walk and stand again for an amputee. Furthermore, other basic functions like sitting, taking stairs, or walking up a hill should be included in the design of a prosthesis. Special requests for sport or similar activities and the appearance of the prosthesis should also be considered.

The connection between the prosthesis and the body needs to transfer the attached forces and hold on to the leg. In case the knee remains after the amputation the main criteria for movement is still guaranteed and needs therefore to be taken advantage of as much as possible. Hereby, the selection of the prosthesis foot and the correct prosthesis construction are important and need to be adjusted to the knee joint.

If the knee is also lost due to an amputation the function of the prosthetic knee is in the main focus. This function is influenced by the single components, the construction of the prosthesis and the leftover performance capabilities of the remaining limb.

Resulting from that the support function of the prosthesis needs to be higher the lower the performance capabilities of the limb are. To guarantee a safe usage of the prosthesis that spares the other joints, does not force the user to use exponential more energy, and offers enough comfort the biomechanical structure of the prosthesis has a small margin for the optimal form.

It is necessary for the amputee to have a safe stance for the knee joint to have a high resistance when standing and when moving a low resistance to gain momentum from the swinging motion of the leg. This results in certain biomechanical criteria for the movement of the knee, like safety for the load management, bending of the knee under pressure, the change of the function between standing and walking, and the controlling of the swinging motion during the process of walking. (Wintermantel, 2009) (Bielmeier, 2010)

3 Prosthesis

The general classification of prostheses is divided into active and passive prostheses. There are numerous types of each variation and there are often types of both that fulfil the same purpose.

The differences between active and passive prostheses is mostly affiliated to the complexity of them. Active prostheses achieve their tasks by using their internal mechanisms and try to replace the original function of the replaced limb without the necessity of external measures.

Passive prostheses on the other side follow a more basic concept and often need either external support to accomplish certain tasks or they only are used as rudimentary replacements of the original limb. (Maat, Smit, & Plettenburg, 2017) (Nayak & Lenka, 2018)

Figure 5 shows a classification of upper extremities prostheses regarding technical features. For the passive prostheses it shows the differentiation between cosmetic and working prostheses and for the active ones there are categorizations for prostheses working with movement generated by muscles or generated by technical actuators.

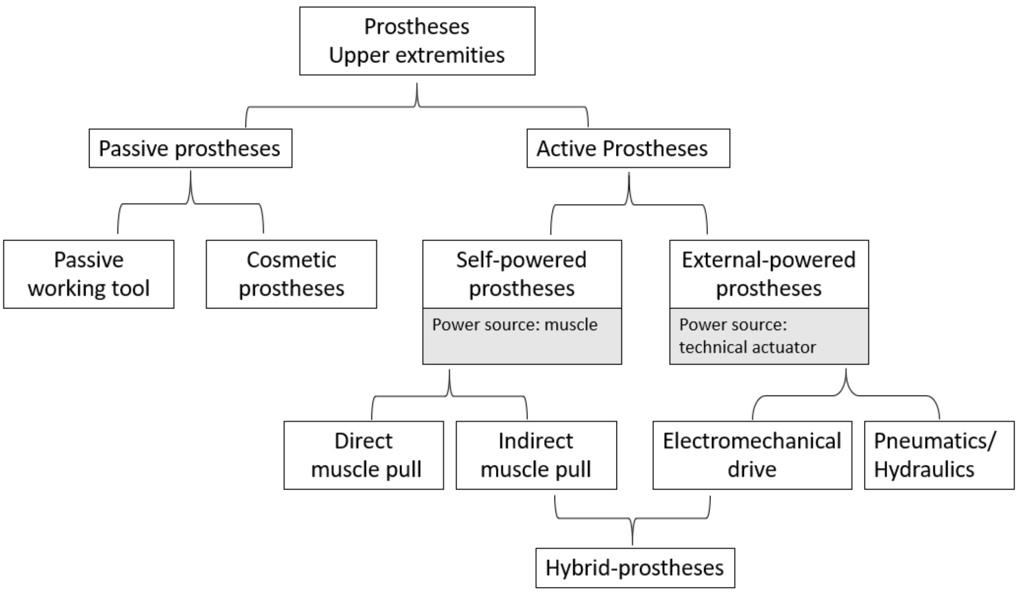

Figure 5: Active and passive prostheses (Wintermantel, 2009)[Translated]

3.1 Passive prostheses

The amount of variations of different passive prostheses is numerous. Due to the individuality and the use of same terms and names for different devices the categorizing of them is difficult and discussions about them are often unclear.

Looking at the example of passive protheses for the hand it is possible to separate them into prosthetic hands and prosthetic tools. The prosthetic hands mostly offer cosmetic appearance advantages and are used for basic activities. Prosthetic tools on the other side have a mechanical appearance and often fulfil a specific task which is usually performed twohanded. Both types can either be static which means they cannot be moved, or they are adjustable and therefore able to perform simple tasks with external help or they can be adjusted to different orientations. For these adjustments either the sound hand or an object from the surroundings is required to perform the desired task.

About one third of the potential prosthetic hand users use a passive prosthesis. Young children and recent amputees are suited better with a passive prosthesis because of the simpler usability. This results in a later change to an active prosthesis.

Passive prosthetic tools usually fulfil a specific task like doing sports or driving a vehicle and they are commercially available for most of these activities. (Maat, Smit, & Plettenburg, 2017)

In figure 6 a few examples for passive prosthetic hands and tools are shown. Hereby, the differentiation of prosthetic hands and tools that are either static or adjustable is combined with the application of each case.

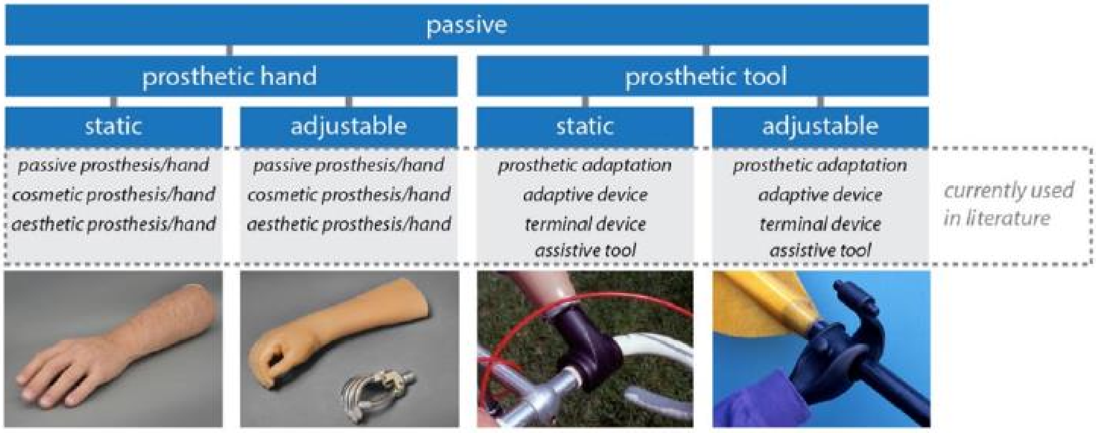

Figure 6: Distinction of prosthetic hand and prosthetic tool [Maat, Smit, Plettenburg, Breedveld(2017); Passive prosthetic hands and tools]

3.2 Active prostheses

The goal of the active prosthesis is to replace a limb or organ in the most natural and capable way. The focus hereby is on the function of the prosthesis. The power of the movement gets either generated by the remaining muscle structure or by a technical actuator. That means the active part is either driven by the own force of the user, or a foreign force.

Self-powered prostheses use either a direct muscle pull, where the prosthesis is directly connected to the muscle and executes its movement powered in that way. The approach of an indirect muscle pull requires a construction that uses traction bandages to create the motion of the device. Combined the self-powered and external-powered prostheses concepts generate a hybrid-prosthesis. This means the muscle is needed to activate a certain external-powered process or it is supported by a motoric generated force.(Wintermantel, 2009)

However, even the most advanced prostheses available today are still unable to fully replace a lost limb. By using new technologies and approaches the quality of life of the user can be improved greatly and the differences are less obvious. Modern robotic prostheses are almost able to perform on par with the corresponding human counterpart.(Bellman, Holgate, & Sugar, 2008)

4 3D-Printing

This chapter focuses on the different variation of 3D-printing as well as the printing of prosthetic devices. Again, the extremities are the basis, that everything relates to.

4.1 Printing techniques

The 3D-printing techniques described in the following chapters belong to the category of additive manufacturing. In this process a part that is based on the data of a 3D model is created by joining materials layer upon layer. These techniques are based on the European Standard EN ISO/ ASTM 52900:2017. (Standardi, 2017)

4.1.1 Binder jetting

By using liquid bonding agent to combine powder materials, by deposing it electively, the binder jetting creates a solid part that is formed out of a powder bed one layer at a time. In figure 7 it is shown how the liquid bonding agent is applied on the powder materials to build the part layer upon layer. (Varotsis, Binder jetting, 2020)

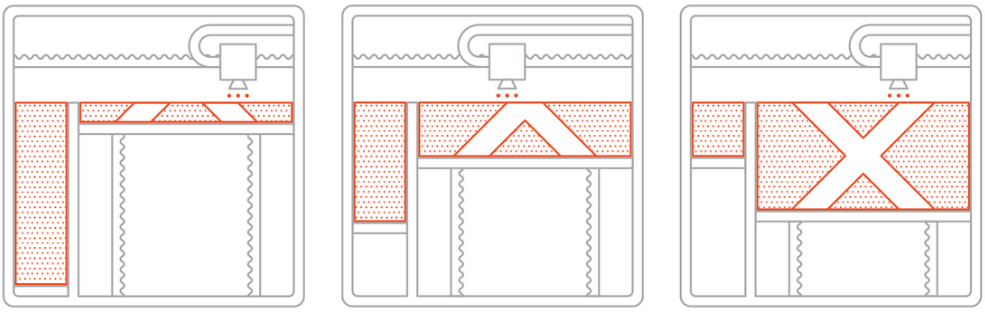

Figure 7: Binder jetting (Varotsis, Binder jetting, 2020)

4.1.2 Directed energy deposition

Directed energy deposition uses focused thermal energy to fuse materials during the deposition by melting them. This focused thermal energy usually is an energy source like e.g. laser, electron beam or plasma arc. (Standardi, 2017)

4.1.3 Material extrusion

To create the desired part this additive manufacturing process dispenses material selectively by a nozzle or an orifice as shown in figure 8. The melted material gets applied layer upon layer on a predetermined path. (Varotsis, Material Extrusion, 2020)

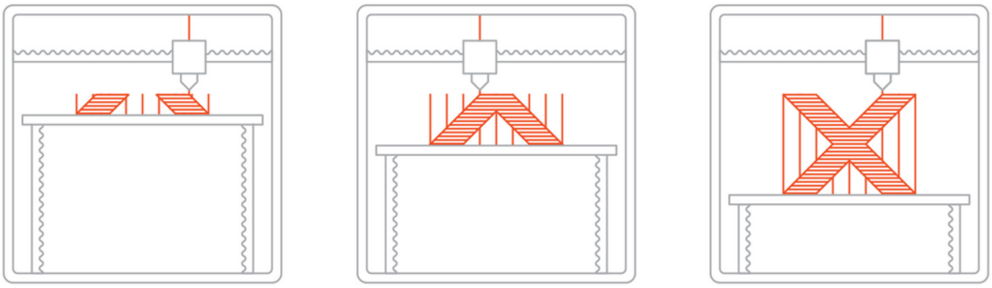

Figure 8: Material extrusion (Varotsis, Material Extrusion, 2020)

4.1.4 Material jetting

In a combination process of depositing building material selectively with a print-head that solidifies under ultraviolet light the part is build layer upon layer. The figure 9 shows how the ultraviolet light is installed right next to the nozzle to instantly solidify the material. (Varotsis, Material jetting, 2020)

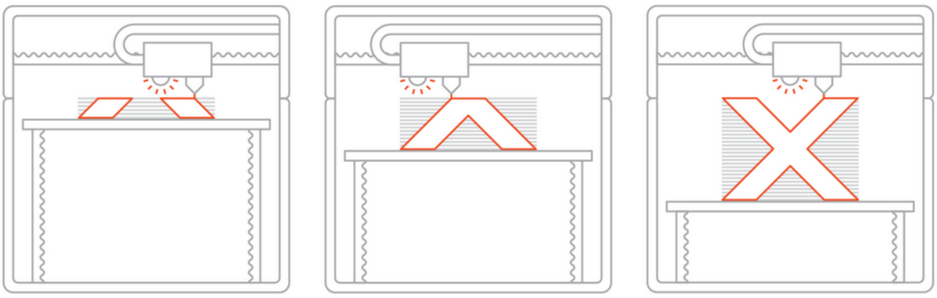

Figure 9: Material jetting (Varotsis, Material jetting, 2020)

4.1.5 Powder bed fusion

This technique requires a beforehand prepared powder bed. Through the usage of thermal energy in selected regions the part is fused out of the bed. In figure 10 it is displayed how the powder bed is transformed into a part by the thermal energy source. (Varotsis, Powder bed fusion, 2020)

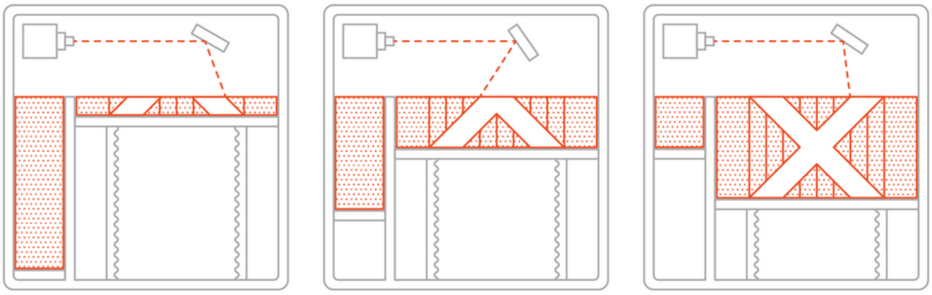

Figure 10: Powder bed fusion (Varotsis, Powder bed fusion, 2020)

4.1.6 Vat photopolymerization

The vat photopolymerization uses an ultraviolet laser beam that creates a part by selectively curing a polymer resin layer by layer. The materials used for that are in a liquid form. This process allows the user to produce parts with a high accuracy or smooth surfaces. In figure 11 the part is built from the bottom and is pulled upwards. (Varotsis, Vat polymerization, 2020)

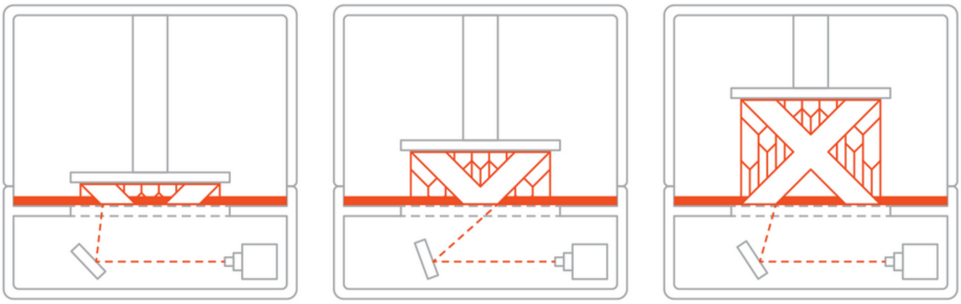

Figure 11: Vat photopolymerization (Varotsis, Vat polymerization, 2020)

4.2 3D – printing of Prostheses

In recent years, the development of 3D-printing of prostheses has increased significantly. There are a lot of people designing and printing devices that are easy to use and fit. The topic is part of multiple scientific researches and there are numerous published papers addressing it. The development of prostheses by individual people and large communities is established. Especially the global community e-NABLE is responsible for the beginning of this developments. In this community multiple individuals from different fields have developed 3D-printed prostheses. The main goal was always to develop a cheap and easily accessible prosthesis. When commercially produced a passive body-powered prosthetic for the hand can cost between $4.000 to $10.000, and an active externally powered prosthetic can cost between $25.000 and $75.000. Compared to that the private 3D-printing offers a solution, where a person with access to a 3D-printer only pays for the material use to produce a prosthesis.

Instead of removing material to create an object, such as in CNC milling, the 3D-printing is an additive manufacturing technique that builds layer upon layer to create an object. One of the several advantages of 3D-printing in comparison with other manufacturing processes is that it is possible to create the product in a single part and therefore no assembly is necessary. This comes with a high design freedom and enables the producer to print complex geometrics that can be personalized without changing the machine. The devices can be produced cheaply and swiftly from start of the design process to the final product, which enables rapid design improvements.

Despite of all the advantages that come with the 3D-printing there are also disadvantages when compared to other manufacturing processes. The mechanical properties are difficult to predict and the resulting strength varies. It is influenced by the fabrication method and the chosen parameters selected based on the printing orientation. The accuracy is influenced by the machine parameters, the material shrinkage and the errors caused by the CAD/CAM software as well as by post processing. Furthermore, the device is bound to the size of the printer the current 3D-printing technology available in larger numbers and for a cheap price does not allow to print larger objects. Also the number of different materials usable for 3D-printing is limited compared to conventional manufacturing. (Kate, Smit, & Breedveld, 2017)

The lack of official guidelines and overview of all the various 3D-printed prostheses make it difficult to produce these in standards and each printing process of a new model has to go under numerous test runs before reaching a desired goal. In figure 12 a few examples show the variety of the different approaches for 3D-printed hand prostheses. (Kate, Smit, & Breedveld, 2017)

Figure 12: Examples of 3D-printed Hand prostheses (Kate, Smit, & Breedveld, 2017)

4.3 Techniques for 3D-printing of prostheses

One of the most common techniques is the fused deposition modelling (FDM), working after the principle of material extrusion shown in chapter 4.1.3. In this procedure the part is printed out of a continuous filament.

Other techniques like the selective laser sintering (SLS) belonging to the powder bed fusion, an additive manufacturing process, displayed in chapter 4.1.5, or the selective stereolithography apparatus (SLA) following the vat polymerization process, pictured in chapter 4.1.6, are using a powder or liquid for printing their parts. (Kate, Smit, & Breedveld, 2017)

4.4 3D-printing material used for prostheses

For 3D-printing of prostheses there is a variety of materials that can be used. The two most used materials are acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA). The FDM printing uses these as a standard material. When using these materials, the devices result in strong parts that withstand the influence of mechanical characteristics over a longer period. The surface of the printed parts on the other hand lacks typical advantages of the human skin that for example help the hand with the grip of objects. For achieving these advantages, a combination of these rigid devices and more flexible materials for specific parts of the device is a possible solution. For that reason, the flexible materials thermoplastic polyurethane and thermoplastic elastomers are used. The FDM printing technique allows, depending mostly on the printer, to use multiple materials at the same time.

By using the polyjetprinting technique it is possible to make a combination of rigid and flexible parts, because of the combination of different materials during the printing process. A typical material used for that technique is FUllCure 729, which is a photopolymer resin.

For printing prostheses with the SLS technique the materials nylon 11 or nylon 12 are used.

SLA can print rigid and flexible materials but not at the same time and the printed devices are made of acrylic plastic.

There are also multiple techniques where the protheses is only partly 3D-printed and the printed parts are combined with different materials like ceramics. Most 3D-printing techniques produce rigid prostheses made out of rigid materials, whereas a combination of flexible and rigid materials enhances the performance and usability of the prostheses. (Kate, Smit, & Breedveld, 2017)

4.5 Durability of 3D-printed prostheses

Despite all the current developments and improvements made in the field of 3D-printed prostheses in the recent years, the devices often show prototype qualities in their final state. Especially when it comes to the durability of the devices it is difficult to predict the overall lifespan of them, also due to lack of proper testing. Overall, there are no long term researches or publications that show how long a 3D-printed prosthesis can be worn before it needs repairs or replacements. The advantage of just reprinting broken parts requires the right circumstances to be effective. The prosthesis user often has no access to a printer and depends therefore on a further person that has access to the technology and capacity to replace the broken parts. This can result in a long replacing process in which the user is unable to use his prosthesis at all. Furthermore, even though the majority of devices is printed with FDM printers, there are some that are not. This requires more time and cost to create a replacement of the broken part.

The strength of the material needs also to be considered when looking at the durability of 3D-printed prostheses. Often there is no official data about the strength of the parts and the complete devices. Especially since the material properties change during the process of the printing. When it comes to FDM printing the material properties show major differences between the printed part and the bulk material. The same goes for SLS and polyjet printing.

The material degradation of 3D-printed prostheses is also not well researched. photopolymer is one of the materials that, when used for prosthetics, degrades at a higher rate than other materials over time. Strength and stiffness of the printed parts are reduced due to the degradation of the material. Therefore, it is important to do further research on the strength and durability of 3D-printed prosthetics. This is needed to ensure a long lifespan, less malfunctions and less maintenance for the devices. (Kate, Smit, & Breedveld, 2017)

4.6 Biomimicry and 3D-printing

When looking at nature there are numerous concepts and ideas that can be copied into the 3D-printing technology. The general concept of 3D-printing, the creating of an object layer by layer, is practiced in nature in multiple processes. Organisms create their structure, like bones, shells, feathers, etc., with a built-to-shape manufacturing process from the bottom to the top. But there are more things than just the concept of the manufacturing process that can be copied.

Like listed in chapter 4.4 the materials used for 3D-printing mostly consists of polymers. These materials come with the disadvantage of a high energy requirement for the production and their toxicity is burden for the environment and the people interacting with it. Therefore, the approach should be, to use renewable, recyclable, waste-sourced feedstocks that achieve similar technical results and are economically reasonable. One of the current ideas for that are starch-based polymers that fulfil these requirements and would fit into this kind of manufacturing approach. Nonetheless, the infrastructure and the technology is not kitted out to support this change to renewable resources at this scale at the moment. (Benyus, 2015)

When it comes to the production of biologically inspired designs is often difficult to produce the complex geometry with the common production methods. 3D-printing offers a solution because of its affinity to the production process of the nature that allows a new set of design constraints that enable the user to work with organic shapes. The process of replicating the natural growing of an organism or object, allows to reproduce almost every structure found in nature by using 3D-printing. (Perry, 2014)

The field of bioprinting is another field that is undergoing rapid advances. Here the technology of 3D-printing is used to print scaffolds for tissues that closely resemble the native microenvironmental properties at the site of implantations. After the application they offer load bearing mechanical properties, nutrient diffusion and cell migration. With the usage of new materials that are synthesized in combination with innovative printing techniques, 3D-printing is becoming more of an effective method used in tissue engineering. For the medical field bionic materials and hybrid 3D-printing approaches have the potential to design tissues that can be used to replace damaged tissue or even help fixing damaged organs. (Do, Khorsand, Geary, & Salem, 2015)

5 Topology Optimization

This chapter represents the combination of the biomimicry, 3D-printing and protheses technology. The topology optimization can be based on an evolutionary algorithm and contains therefore the concept of optimizing an object following the inspiration of nature. The approach of optimizing a part in a similar manner organism grow, results in an application of biomimicry for the design process of prostheses. (Hu, Gadipudi, & Salem, 2018) (Kobayashi, 2010)

5.1 Fundamentals

The overall concept of the topology optimization describes a process that reshapes a design in a simulation to create the lightest structure capable and at the same time resists forces applied to the model. With this method it is possible to maximize the stiffness of components, while reducing the mass of it to a desired value. This means depending on the objective there is either the option to reduce the mass to a specific value or to minimize the weight as much as possible. (Altair Engineering, 2019)

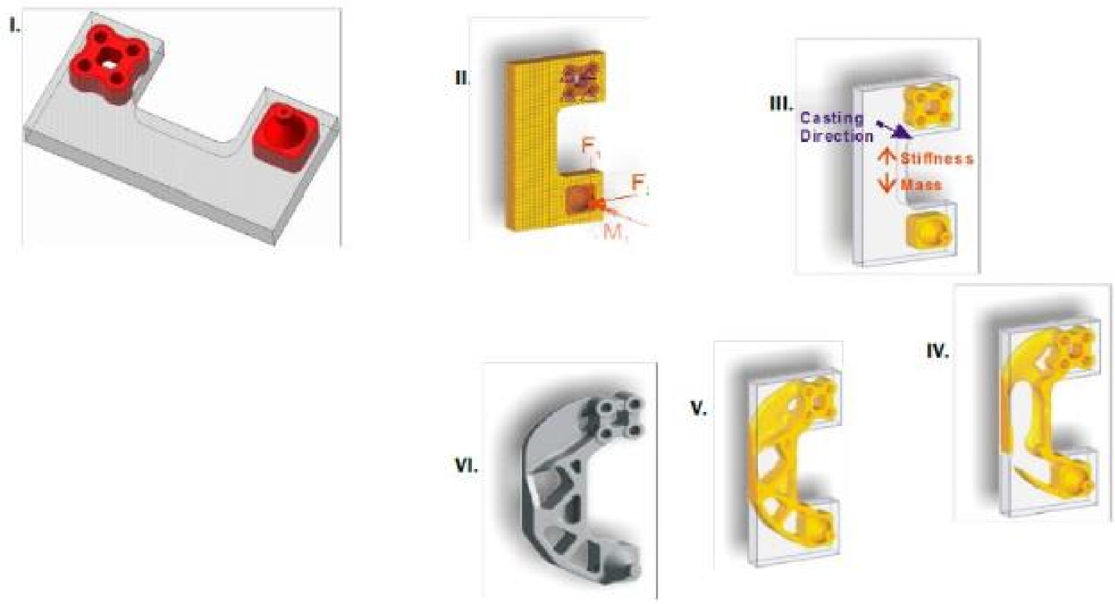

Figure 13: Typical optimization working steps (Altair Engineering, Inc., 2018)

The figure 13 shows in multiple steps the entire sequence of the Topology optimization process. The first step is to define the maximum design space and the non-design areas. Non-design areas are not changed during the optimization, but it can be modified in the original CAD model. To maximize the efficiency of the optimizer it is advantageous to choose a large initial design space with a simple geometry without trying to influence the later final shape.

For the second step it is necessary to build a finite element model based on the starting geometry of the first step. This provides information about the overall structure of the component. Theses information contain for example, stresses, and location of stress concentrations but also the magnitude of displacements. Furthermore, this information is used in the optimization.

In the third step the optimization problem needs to be defined. In case of topology optimization, it has always to be handled in combination with the reduction of the volume and mass or it has to be reduced to a desired amount. Hereby it is important that the initial boundaries on the displacement are set correctly.

The fourth step is the execution of the optimization. It needs to be checked if the design constraints are violated and if the optimization has converged.

The last two steps include the post-process of the results. Here the design proposal is supposed to be interpreted and comprehended. In case of a satisfying result with the design configuration the new geometry can be used as a reference solution for other CAD designs. (Altair Engineering, Inc., 2018)

5.2 Topology optimization for prostheses

When it comes to the development of lower extremities prostheses, one of the biggest challenges is the design of a light-weight structure that is able to withstand high loads occurring during the motion of the prosthesis. Therefore, topology optimization can help to assist the development of prostheses components that are lighter and more compact, while at the same time improving their overall efficiency and performance.

By receiving a higher strength through the application of geometry optimization rather than the use of high-strength materials, like typically used aerospace alloys, it is possible to develop lighter and more cheaper devices. The cost reduction by implementing cheaper materials or choosing of less expensive manufacturing processes like 3D-printing require that these prosthetic devices continue to withstand high loads and provide enough strength to follow existing international standards.

The success in other industrial fields of the topology optimization as a useful method to reduce mass and improving the performance of mechanical parts can also be applied for prosthetic design and optimization. Even established designs of prostheses can be modified and further improved. (Reist, Andrysek, & Cleghorn, 2010)

5.3 Altair Inspire

Altair Inspire is a software that enables the usage of a numeric simulation, that meet structural requirements by placing material in an optimal manner only where it is needed. Furthermore, inspire offers the possibility to create, modify, and defeature solid CAD models. The generated structures are also manufacturable provided that the manufacturing process was chosen.

Another implemented part of the software is the customization of materials and a selection of optimization tools such as objectives, displacement and stress constraints, loads and surface smoothing of the optimized concept geometry. For an analysis of the results generated by the software it offers multiple ways of examining structures of designed parts by using finite element calculations. (Altair Engineering, 2019)

5.4 Optimization of an example

For the process of the optimization the software Altair Inspire 2019.4 is used. It includes the option for geometrical editing and OptiStruct as the finite element analysis (FEA) solver and optimizer. The possibility for post-processing is also included.

The CAD geometry shown in figure 14 is a simplified example, which is chosen to explain the process of the optimization. It also represents a rudimentary version of a finger to demonstrate the advantages of the topology optimization for the design of a prosthesis and a possible application.

In the first step a design space and design parts are defined. The grey parts represent the non-design space and the brown part shows the design space. The design space on the left side is exposed to a pressure and the design space on the right side represents the support bearing. Therefore, the decision to choose these areas as design space is attributed to the necessity of them not changing after the optimization, so they can fulfil their task of absorbing the forces. Another vital step in the beginning of the pre-processing is the definition of materials. Regarding the desired 3D-printing of the part later on the plastic ABS was chosen, due to its common usage in that field [4.4].

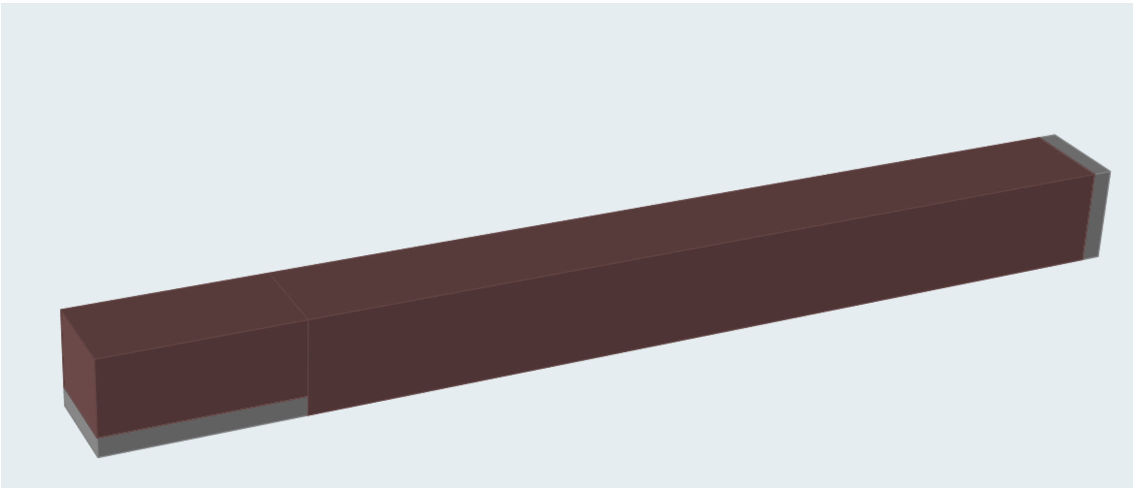

Figure 14: Simplified Geometry with design space case A

During the pre-processing, the three parameters design variables, objectives, and constraints need to be specified for a successful optimization. For this optimization, the objectives and constraints were chosen with the goal to maximise the stiffness of the part and reduce its mass. To receive a better result, the determination of the objectives and constraints requires performing a FEA on the part beforehand.

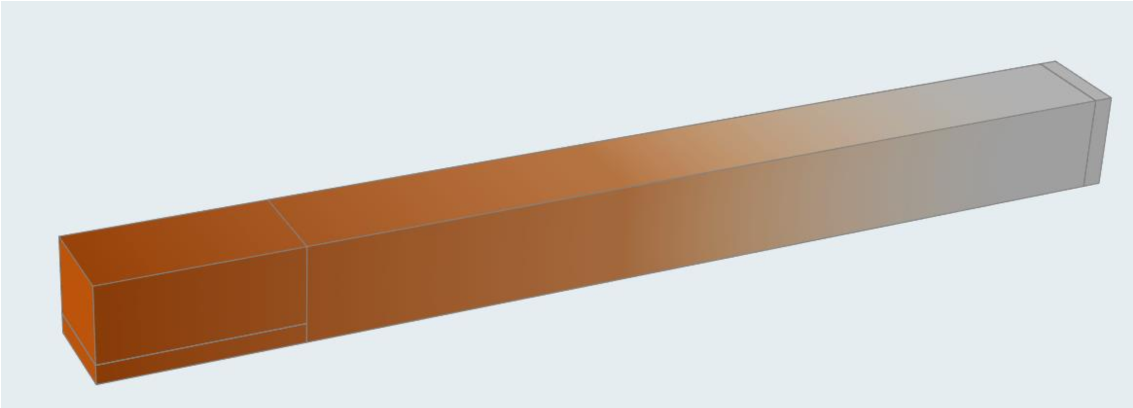

Figure 15: FEA of the part case A

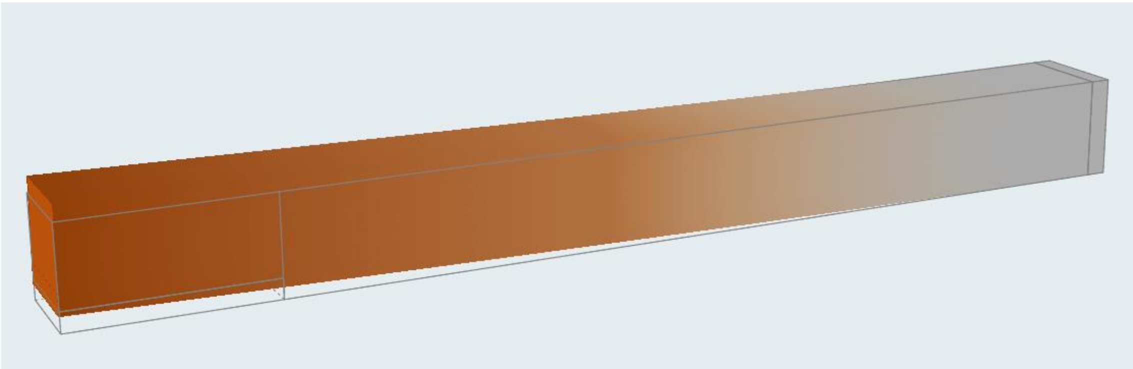

Figure 16: FEA of the part with maximum displacement case A

The analysis of the original part, performed before the optimization, shown in figure 15 and figure 16 is needed to receive information about the performance references for the optimized design. The orange areas show where the applied pressure creates a larger deformation and the effect of displacement for the part.

The corresponding mathematical statement used by the software to determine the structural optimization is:

$$\min f(x) = f\{x_1, x_{2,} \ldots , x_n\}$$

Subject to

$$g_j(x) \leq 0 \qquad j = 1, \ldots m$$

$$x_i^L \leq x_i \leq x_i^U$$

f(x) describes here the objective function, g(x) the constraint functions, and x is a design variable. (Altair Engineering, Inc., 2018)

The topology optimization processed by the software uses the solid isotropic material with penalization (SIMP) element density method. Hereby the relative density ρ varies between zero and one, which influences the elasticity tensor of the element

$$\frac{E}{E_0} = \left(\frac{\rho}{\rho_0}\right)^p$$

in this case *E* is the elastic modulus of the element, ρ is the relative element density and *p* describes the penalization factor. (Bendsoe & Sigmund, 2003)

Figure 17 shows the optimization results viewed as element density iso-plots. Hereby the elements in the design space are at a certain threshold density. In this example the optimization objective is to reduce the total design space volume to *30%*, therefore this numerical value was taken as the cut-off threshold.

Figure 17: Optimized part case A

When looking at the results it is noticeable that the optimization changes the structure of the part in a way, which abandons the desired composition of it. This can either be resolved by adjusting the geometry in the post processing and manually create a solution in a CAD program, or the design space can be adjusted beforehand to achieve better results. In this case the design space is expanded to the entire cross-section of the part shown in Figure 18: Geometry with different design space.

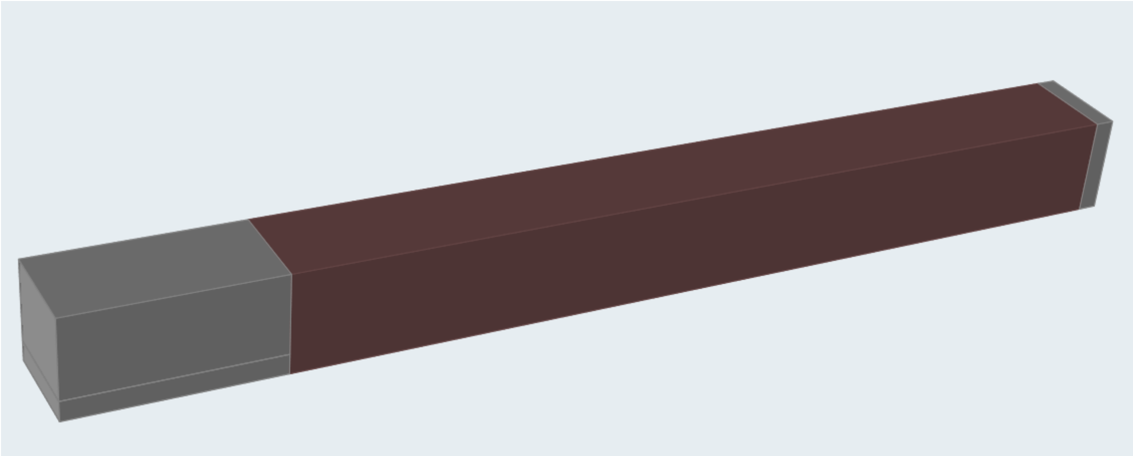

Figure 18: Geometry with different design space case B

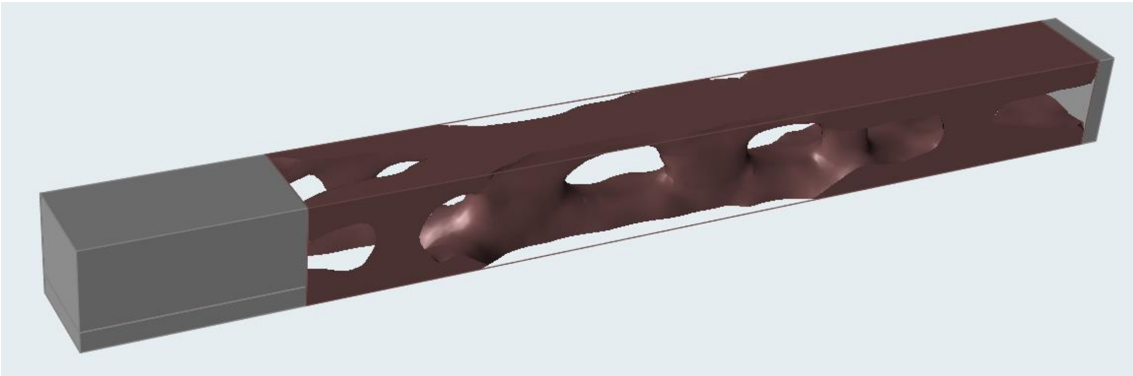

Figure 19: Optimized part with different design space case B

By choosing a different design space the results show a similar result compared to the prior optimization. The objective of maximizing the stiffness while reducing the mass leads to the structure shown in figure 17 and figure 19, which mainly differ in the transition of the design space into the non-design space.

After the optimization, the results need to be post-processed. Another FEA for the now optimized part is necessary to receive information about the deformation of the part. This result is compared with the result of the FEA of the not optimized part. In figure 20 and in figure 21 the deformation of the part and the maximum displacement are shown. The orange parts show the higher deformation resulting from the applied pressure at the end of the segment. The difference in the maximum displacement between the original part shown in figure 15 and that of the optimized part displayed in figure 20 result in below *20 %* and are in correlation with the objective of reducing the design space volume to *30 %.*

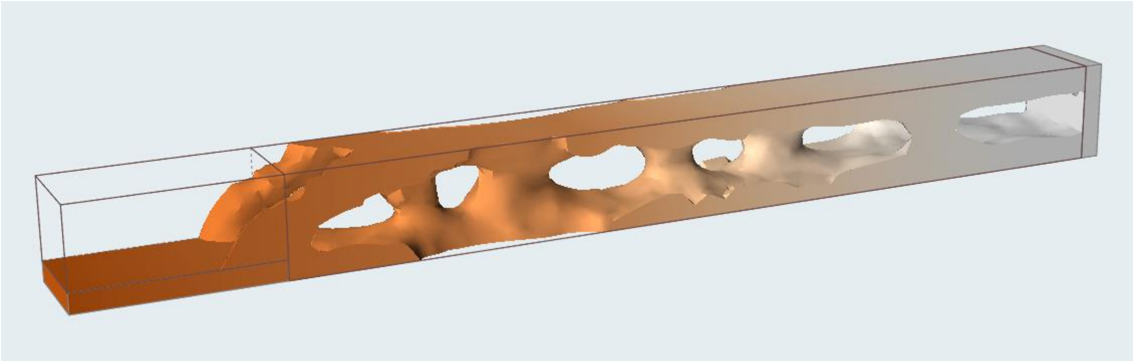

Figure 20: FEA of the optimized part case A

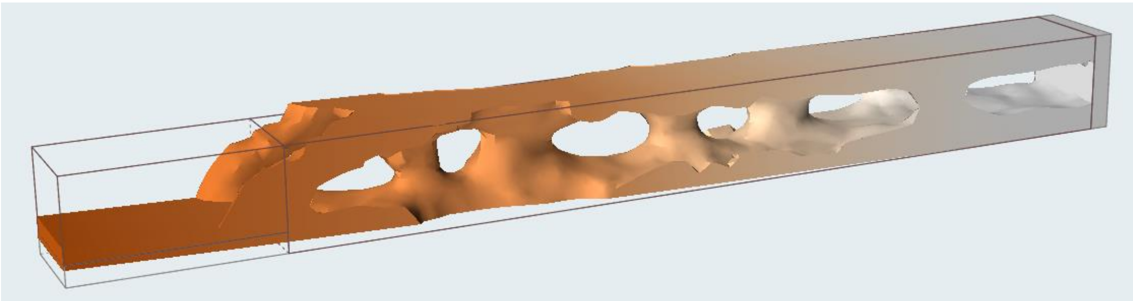

Figure 21: FEA of the optimized part with maximum displacement case A

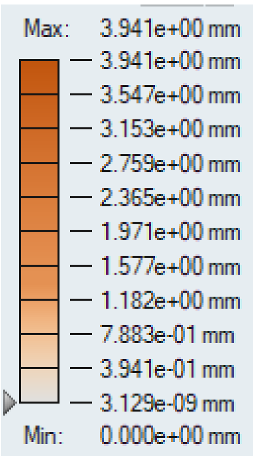

Figure 22: Displacement of the optimized part case A (orange colour is related to the colouring of the FEA)

Again, the following figures showcase the scenario for the larger design space and its deformation after the optimization. The results variate here to a minimum and show that the calculation made by the software results in similar outcomes regarding the displacement.

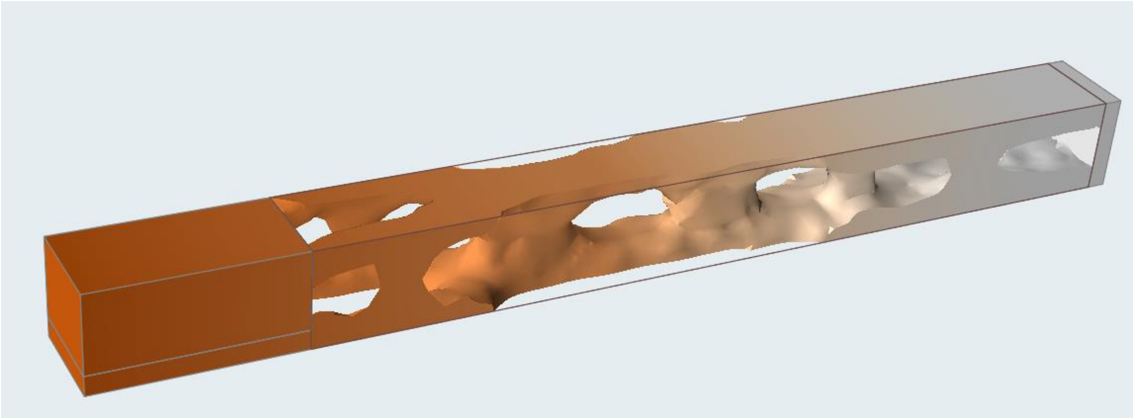

Figure 23: FEA of the optimized part with different design space case B

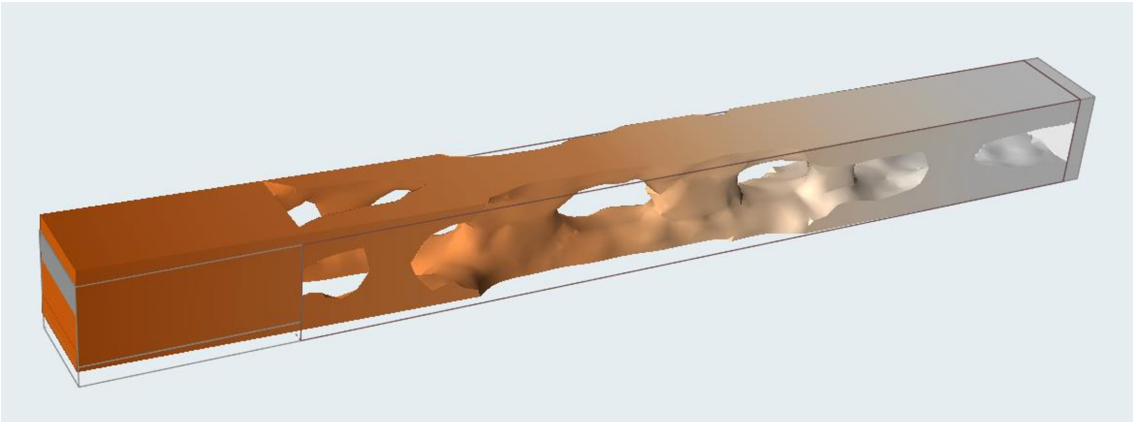

Figure 24: FEA of the optimized part with maximum displacement and different design space case B

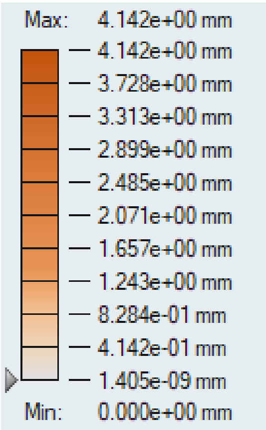

Figure 25: Displacement of the optimized part with different design space case B (orange colour is related to the colouring of the FEA)

Looking at the differences of the actual displacement in the figure 22 and figure 25 it shows that the values do not differ much and are roughly around *5 %*. This is also affiliated to the parameters for the minimum thickness or the element, which variate regarding the original part and its properties.

The optimized part can now be exported into a CAD program to create a discrete geometry by manually adjusting the reduced segments into a useful construction. Hereby the core structure should be as close as possible to the results of the optimization to receive a part that fulfils the objectives set before the optimization. Furthermore, the usefulness of the part must be evaluated. The main requirements still need to be accomplished and the overall application of the device must work in the context of its planned installation into a device.

5.5 Optimization of a prosthetic limb socket

When applied on a real prosthetic device the optimization helps to shape the design by reducing the material, while maximizing the stiffness of the part. For this method it is important to do a detailed post-processing of the optimization process to guarantee a useful improvement of the part. When looking at the results of the optimization the desired functionality of the part should still be intact.

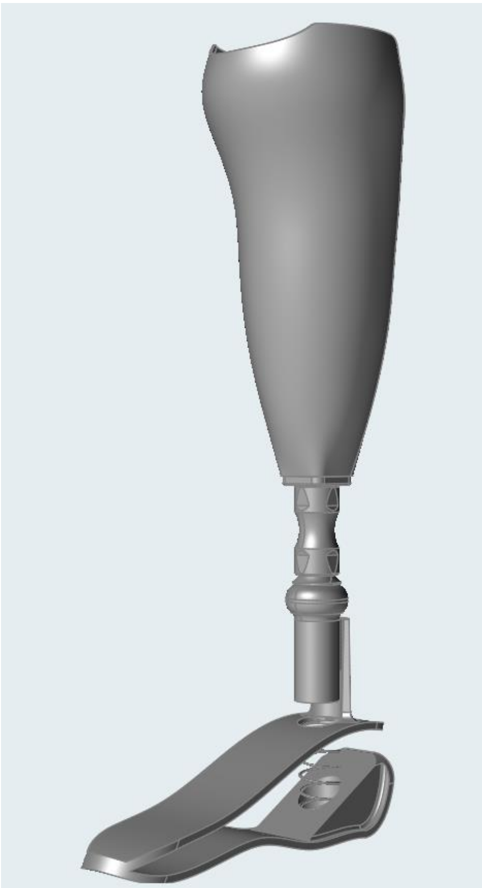

Figure 26: Below knee-prosthesis (Tsigonias, 2018)

The device in figure 26 is a below-knee prosthesis that was gathered from GRABCAD. This is an open source software website that offers free models of prostheses. The prosthetic limb socket shown in is a single component of this device and is the part to be examined.

By selecting the upper rim and lower connection surface as design space the segments of the limb socket responsible for its function stay intact. Hereby, the design space on top of the part is selected as the bearing. With the information from chapter 2.2.2 the load case for a standing leg is selected. Assuming the person has a weight of around *80 kg* in combination with the surface area of *324 mm²*, where the socket connects to the rest of the prosthesis, the applied pressure at the bottom of the part is approximately *1.2 MPa*. The material used in the simulation for the limb socket is ABS to enable 3D-printing as the production process.

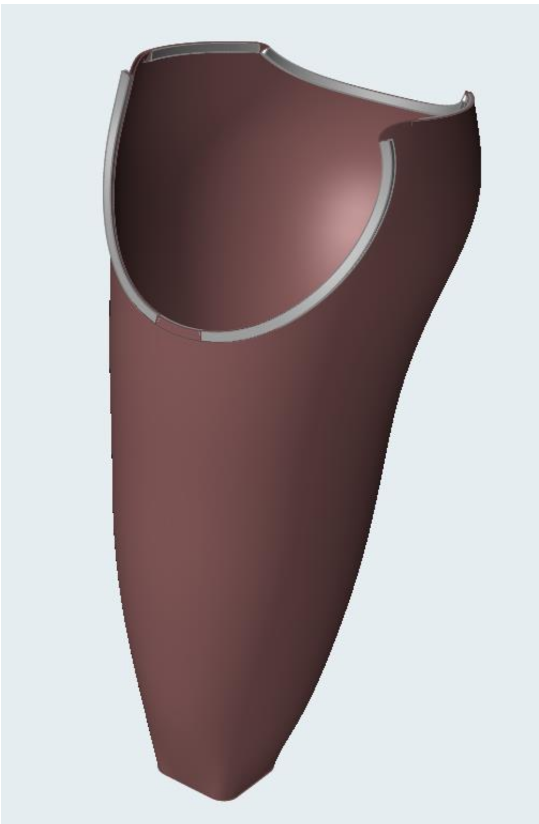

Figure 27: Prosthetic limb socket (Tsigonias, 2018)

Like mentioned before the objectives of the optimization are the maximizing of the stiffness and the reducing of the mass. This results in the optimized part shown in figure 28 The mass target for the material reduction is at *30 %* and leads to the grid like structure of the socket.

Figure 28: Prosthetic limb socket after optimization in both side views

This result represents only the load case of the standing process. There is no motion or moment as a load included in this scenario. When looking at the structure this needs to be considered when the geometry is exported to a CAD program for adjusting the part into a producible object. Moreover, the function of the part needs also to be tested, to assure that when utilized there are no malfunctions or inconveniences occurring during the usage. This means a thoroughly testing phase with a user of the prosthetic devices is necessary to classify the usefulness of the optimization and to see if the optimization is helpful. Furthermore, it needs to be tested if this part is printable in this variation and if there are more suitable versions for this production process.

6 DISCUSSION

The goal of this thesis was to find helpful implementations of biomimicry in the design and production process of prostheses. Especially in combination with 3D-printing the influence on these production processes by biomimicry was in the focus of this work. Due to the COVID-19 restrictions the worked-out results of the project could not be tested in a practical context. The original plan included a 3D-printing of the optimized components and an examination of the printed parts. Here the effects of different materials, printing techniques and designs were supposed to be tested and analysed.

The complex structure and functionality of the human body cannot easily be transferred into a working prosthesis. There are multiple approaches for replacing a lost limb and the variety of different prosthetic devices make it difficult to identify a standard for them. Therefore, at the same time the possibilities to improve them by implementing ideas from the nature are diverse and are suitable for new ideas and prototypes.

The recent uprising of 3D-printing technology and its implementation in modern production cycles requires a different way of thinking compared to traditional production processes. Techniques like the topology optimization are helpful in improving the design and the construction of 3D-printed parts. The technical aspects of weight reduction and the increasement of the stiffness achieved by this optimization, result in optimized parts that cannot easily be produced with traditional manufacturing processes. 3D-printing enables a production of theses complex parts and structures with its additive manufacturing process.

The implementation of biomimicry in the design of a prosthesis in form of the topology optimization shows the possibilities that occur, when the fields of biomimicry, 3D-printing and prostheses technology are combined. There are still numerous improvements that can be copied by nature to enhance the production processes, the quality and the technical properties of prostheses, while reducing the price, increasing the comfort for the user and its availability.

REFERENCES

Altair Engineering, I. (2019). *Simulation-Driven Design with Altair Inspire.*

Altair Engineering, Inc. (2018). *Practical Aspects of Structural Optimization A Study Guide.* https://altairuniversity.com/free-ebooks/free-ebook-practical-aspects-of-structural-optimization-a-study-guide/.

Bellman, R., Holgate, M., & Sugar, T. (2008). *Design of an Active Robotic Ankle Prosthesis with TwoActuated Degrees of Freedom Using Regenerative Kinetics.*

Bendsoe, M. P., & Sigmund, O. (2003). *Topology Optimization: Theory, Methods and Applications.* Berlin: Springer-Verlag.

Benyus, J. (2015, 10 29). *Nature Is The Ultimate 3-D Printer: Can We Make Our New Manufacturing As Clean?* Retrieved from FastCompany: https://www.fastcompany.com/3052096/nature-is-the-ultimate-3d-printer-can-we-make-our-new-manufacturing-as-clean

Bhushan, B. (2009). Biomimetics:lessons from nature - an overview. *Philosophical Transactions*, pp. 1445-1486.

Bielmeier, A. (2010). *Aktueller Stand der Prothesentechnik.*

Do, A.-V., Khorsand, B., Geary, S., & Salem, A. (2015, 06 10). *3D Printing of Scaffolds for Tissue Regeneration Applications*. Retrieved from PMC: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4597933/

Hu, Z., Gadipudi, V., & Salem, D. (2018). *Topology Optimization of Lightweight Lattice StructuralComposites Inspired by Cuttlefish Bone.*

Kate, J., Smit, G., & Breedveld, P. (2017). *3D-printed upper limb prostheses: a review.*

Kobayashi, M. (2010). *On a biologically inspired topology optimization method.*

Kulkarni, A., & Saraf, C. (2019). *Learning from Nature: Applications of Biomimicry in Technology.*

Maat, B., Smit, G., & Plettenburg, D. (2017). *Passive prosthetic hands and tools: A literature review.*

Nayak, S., & Lenka, P. (2018). *Passive Biomimetic Prosthesis.*

Perry, D. (2014, 02 27). *3D Printing Biomimicry Leads to Righteous Ripping*. Retrieved from SolidSmack: https://www.solidsmack.com/fabrication/3d-printing-biomimicry-leads-righteous-ripping/

Reist, T. A., Andrysek, J., & Cleghorn, W. L. (2010). *Topology Optimization of an Injection Moldable Prosthetic Knee Joint.*

Sani, M., Muftah, F., & Siang, T. (2013). *BIOMIMICRY ENGINEERING: NEW AREA OF TRANFORMATION INSPIRED BY THE NATURE.*

Standardi. (2017). Additive manufacturing. General principles. Terminology (ISO/ASTM 52900:2015).

Tsigonias, G. (2018, 09 26). *Below-knee Prosthesis*. Retrieved from GRABCAD Community: https://grabcad.com/library/below-knee-prosthesis-2

Varotsis, A. B. (2020, 06 10). *Binder jetting*. Retrieved from 3D HUBS: https://www.3dhubs.com/knowledge-base/introduction-binder-jetting-3d-printing/#what

Varotsis, A. B. (2020, 06 10). *Material Extrusion*. Retrieved from 3D HUBS: https://www.3dhubs.com/knowledge-base/introduction-fdm-3d-printing/

Varotsis, A. B. (2020, 06 10). *Material jetting*. Retrieved from 3D HUBS: https://www.3dhubs.com/knowledge-base/introduction-material-jetting-3d-printing/

Varotsis, A. B. (2020, 06 10). *Powder bed fusion*. Retrieved from 3D HUBS: https://www.3dhubs.com/knowledge-base/introduction-metal-3d-printing/

Varotsis, A. B. (2020, 06 10). *Vat polymerization*. Retrieved from 3D HUBS: https://www.3dhubs.com/knowledge-base/introduction-sla-3d-printing/

Wintermantel, E. (2009). *Medizintechnik.* Springer.

FIGURES