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Mechanical design of affordable below-elbow prosthetic for kids.

LAB University of Applied Sciences
Bachelor of Mechanical Engineering and Production Technology
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I would like to thank my mother at the first place, as all this would have been absolutely impossible without her, my partner Mariia who has always been around to help and support me. And all my other friends who cheered me along the way. Their trust helped me to go through every second of these splendid three years of studies.

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And all this science
I don't understand
It's just my job five days a week

Elton John

Abstract

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Abstract

Kids grow fast and often change of prosthetics is required. Modern prostheses with advanced control and power actuators cost a lot, while simpler versions are inconvenient with limited functionality.

The thesis work builds up a product development approach to develop a concept of an affordable below-elbow prosthesis for kids, using additive manufacturing. Understanding customer needs is an important part of product development that defines what should be done. Generating concepts using sketches and implementing the selected concept as a prototype helps to choose the most viable ideas.

The final concept provides new solutions on how to increase the agility of body-powered prosthetics alongside certain design challenges to be solved before using the concept for a real product.

Keywords

Prosthetic, additive manufacturing, amputees, product development, mechanical design

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LIST OF SYMBOLS AND ABBREVIATIONS

ABS	Acrylonitrile butadiene styrene
AM	Additive Manufacturing
CAD	Computer-Aided Design
DFA	Design for Assembly
DFM	Design for Manufacturing
DFMA	Design for Manufacturing and Assembly
DOF	Degree Of Freedom
EBM	Electron Beam Melting
FDM	Fused Deposition Modelling
FFF	Fused Filament Fabrication
Kg	kilogram
LENS	Laser Engineering Net Shaping
LOM	Laminated Object Manufacturing
PETG	Polyethylene terephthalate glycol
PC	Polycarbonate
PLA	Polylactic acid
SL	Stereolithography
SLS	Selective Laser Sintering
STL	Standard Triangle Language
3D	three dimensional
3DP	3D Printing (Binder Jetting)

1 Introduction

The thesis's **main goal is to develop a scalable body-powered below-elbow arm prosthesis for children**. Arm prostheses are a complex matter themselves but designing them for children brings even more challenges. First, children grow fast, therefore, an often change of a prosthesis is required. A child can grow up without a prosthesis; however, it may negatively affect how muscles and the body develop.

The second important aspect of the research work is to study DFM for additive manufacturing. The product is planned to be printed using 3D printing technologies and assembled by potential users or their parents. Desired physical scalability of the product is also a challenge. To overcome these challenges and provide a solution that will satisfy most of the potential customers, 3D printing with polymers should be reviewed and DFMA techniques applied. The latter help to design products that are efficient in manufacturing and simple in assembly; both aspects are critical for the prosthetic under development because manufacturing and assembly will be performed by an end-user.

The last aspect to be covered is product development principles and the use of them in designing a prosthesis. The thesis idea is to develop a product that will be accessible and aimed at certain categories of people. These categories and their needs will be studied thoroughly, and a list of needs will be formulated. Not only product development practices will formulate customers' needs, but they will also help to organize the workflow of development.

1.1 Prosthetics and its history

1.1.1 A brief introduction to the history

Prostheses have always been an important part of human society. Sometimes children are born without one or more limbs, and sometimes arms and legs are lost during wars and conflicts. Luckily, limbs are not “vital” human organs, unlike a heart or a brain. Therefore, it is possible to live without arms or legs (Klopsteg & al. 1954).

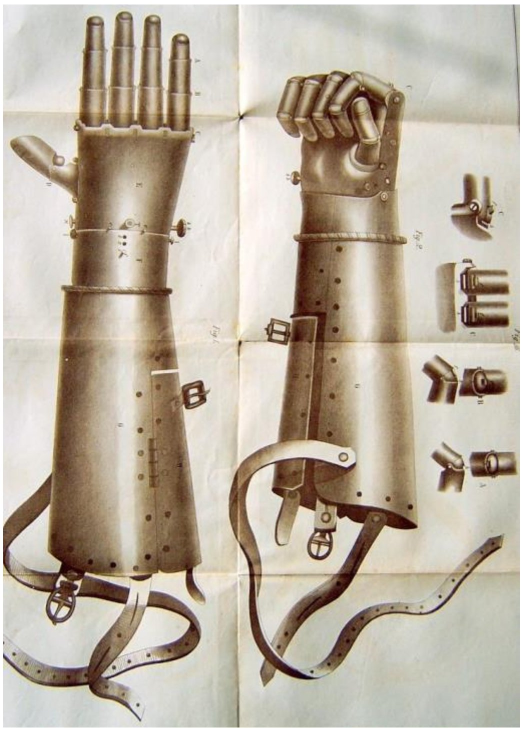

Figure 1. Von Berlichengen prosthetic arm (Wikipedia 2022a)

First prostheses date back to ancient times, but the first prosthetics with basic functionality were being created between the fifteenth and seventieth centuries. They were made mainly by armorers who already had had experience with products of similar shape. One of the most famous examples is a metal hand of Götz von Berlichengen made in around 1510 and displayed in Figure 1.

The prosthesis already resembles its modern successors and has the most important parts: a prosthetic interface and a terminal device (palm with fingers). The terminal device had two modes for grasping: the palm is either opened or closed.

World Wars I and II boosted the development of prosthetics, bringing lighter materials like plastics and making prosthetics more individual. Later, as electronics developed, prostheses that are controlled with muscle pulses and equipped with servomotors occurred. Nowadays there are plenty of different prosthetics available for different prices, but more advanced technologies cost more.

1.1.2 Arm prostheses classification

Arm prostheses can be classified by how they are operated (Trent & al. 2020):

- Unpowered or passive prostheses

- Body-powered prostheses
- Externally powered prostheses
- Hybrid systems.

Unpowered prostheses mostly serve cosmetic needs and are often used for socializing occasions (Kutz 2003). The engineering perspective can prioritize prehension, but it should be kept in mind that prosthetics are used by humans. Humans have a need for “usual appearance”. This kind of prostheses is called *cosmeses*.

Body-powered prostheses, as their name assumes, use shoulder muscles to actuate a terminal device. Prostheses of that kind can be considered to have rather simple mechanics, but it is not necessarily a bad thing: ease of maintenance, ease of repair, and intuitive understanding of operating principles are great advantages of body-powered prosthetics. Bowden cable is the type of cable that is used to transmit forces from shoulders. Modern body-powered prosthetic with two terminal devices is shown in Figure 2.

Figure 2. Body-powered prosthesis (Ottobock 2022)

Externally powered prostheses use servomotors motors and myoelectric sensors. The latter are a special type of sensors that measure the electric properties of muscles. Based on the power of the signal, control electronics send commands to the motors. The power source is a crucial part of prostheses. This type of prosthesis started gaining popularity after World War II, as the components became more available.

Finally, hybrid devices represent mix of body and externally powered solutions. The solution targets a wearer with high level of amputation: for example, above an elbow or a bilateral amputation. Combining both body power and external power sources gives better control over both hands and helps to differentiate the arms. However, this type of prosthetics may not be relevant to the thesis work, because of its complex nature and potential high costs.

1.1.3 Prehension

Prehension is an action of grasping. It is the most important function provided by a hand. Therefore, prehension is expected to be implemented in a prosthesis (Klopsteg & al. 1954).

Complex movement of fingers and palms depend on muscles. Muscles help to control force and position of fingers, providing various range of opportunities: from holding a tennis rocket to grabbing an egg or playing the piano. Because it is yet impossible to recreate muscles, offering as much natural functionality as possible is one of the key elements in making an arm prosthesis.

The product that will be developed during the thesis work might have big number of interchangeable tools to compensate lack of functionality provided by fingers. Replicating fingers and their movement is more complex and requires more resources than using different terminal devices. Moreover, artificially designed fingers lack functionality compared to the real fingers due to worse control possibilities. Considering these facts, use of additional terminal devices seems preferable.

1.2 Additive manufacturing

1.2.1 Technology overview

Additive manufacturing originated from rapid prototyping. Additive manufacturing main principle is that it allows parts to be fabricated directly from a CAD model without planning manufacturing process beforehand (Gibson I, Rosen D & Stucker B 2015). Simplicity of additive manufacturing is provided by making parts by layers, where thickness of a layer is the main limiting factor.

After 3D model is created and converted to STL file, which is a common file type for all CAD programs, it is post-processed to create special code (G-code) that controls movement of the printer. The extruder moves above the print sheet and emits molted filament on the sheet. Often auxiliary structures are printed to support part layers that overhang excessively. Printer's parts are demonstrated in Figure 3.

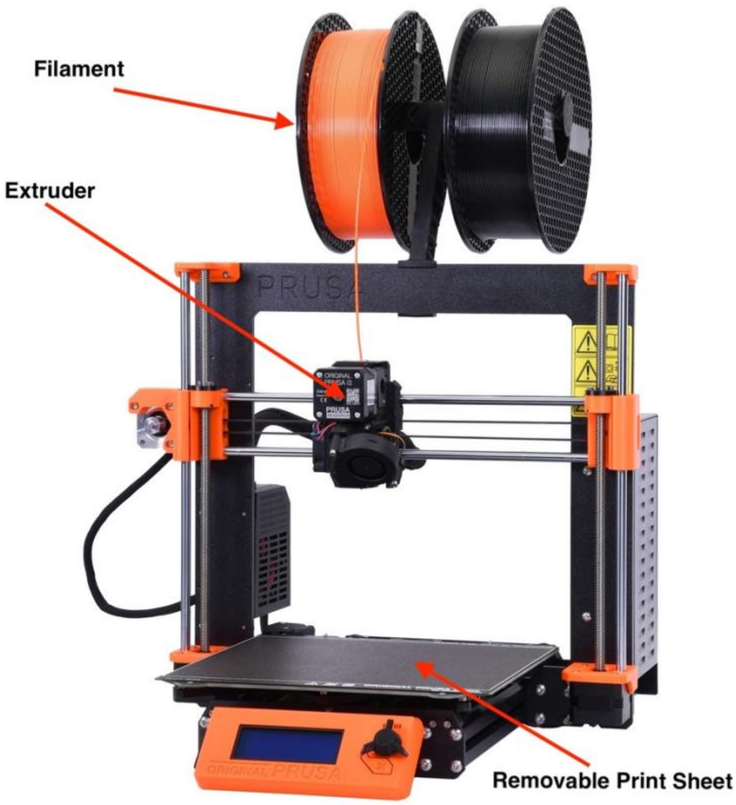

Figure 3. Prusa 3D printer (Prusa Research 2022)

Additive manufacturing is suitable for different materials in different forms: polymeric filaments in solid shapes or metal powder will work for printing; however, the way material will be extruded is different. More strictly, there are three main classifications for additive manufacturing that are presented in Figure 4.

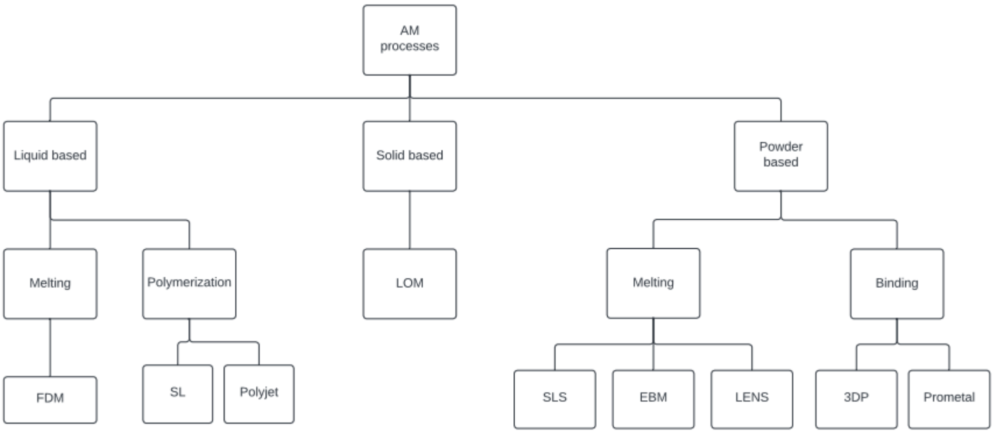

Figure 4. 3D printing processes (Kruth 1991)

The product under development will be aimed to be affordable, hence it will be recommended to users to utilize the most popular printers. The most common process used in hobbyist printers is FDM, often referred to as FFF too. The solid filament is supplied to extruder where it is then melted and put on a print sheet. Process schematics are shown in Figure 5.

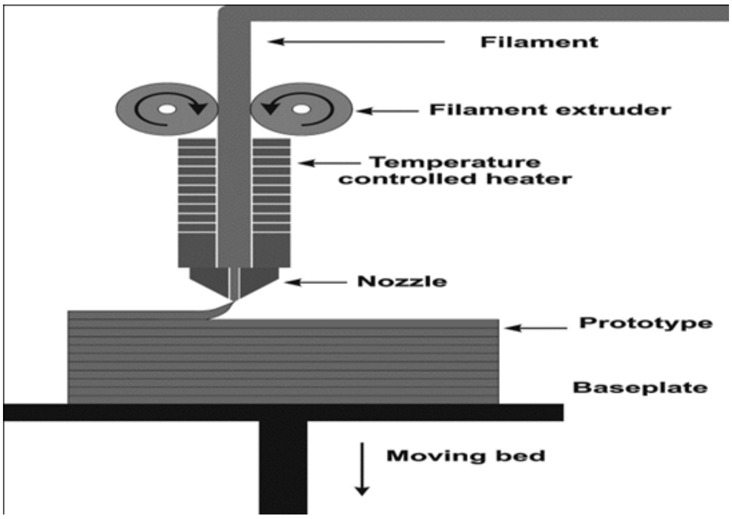

Figure 5. FDM process (Olivera & al. 2016)

1.2.2 Materials for additive manufacturing

As was mentioned earlier, polymers, metals and ceramics are materials to be used in additive manufacturing.

	Amorphous	Semi-crystalline	Thermoset	Material extrusion	Vat polymerization	Material jetting	Powder bed fusion	Binder jetting	Sheet lamination	Directed energy deposition
ABS [Acryonitrile Butadiene Styrene]	X			X						
Polycarbonate	X			X						
PC/ABS Blend	X			X						
PLA [Polylactic Acid]	X			X						
Polyetherimide (PEI)]	X			X						
Acrylics			X		X	X				
Acrylates			X		X	X				
Epoxies			X		X	X				
Polyamide (Nylon) 11 and 12		X					X			
Neat		X					X			
Glass filled		X					X			
Carbon filled		X					X			
Metal (Al) filled		X					X			
Polymer bound	X	X		X						
Polystyrene	X						X			
Polypropylene		X					X			
Polyester ("Flex")							X			
Polyetheretherkeytone (PEEK)		X		X			X			
Thermoplastic polyurethane (Elastomer)				X			X			
Chocolate		X		X						
Paper									X	
Aluminum alloys							X	X	X	X
Co–Cr alloys							X	X		X
Gold							X			
Nickel alloys							X	X		X
Silver							X			
Stainless steel							X	X	X	X
Titanium, commercial purity							X	X	X	X
Ti–6Al–4V							X	X	X	X
Tool steel							X	X		X

Figure 6. Commercial materials directly processed by AM (Bourell & al. 2017)

However, polymers are the easiest and the most common material to use for hobbyist printers. 3D printers produced by Prusa Research support wide range of thermoplastics for printing. The short-listed materials are presented in Figure 6 and listed below:

- PLA
- PETG
- ABS
- PC
- Flex.

Materials to be used for the final product will be selected after the final concept is selected and design phase is started.

1.2.3 DFMA for additive manufacturing

DFM can be defined as a design process where manufacturing is taken into account throughout development. When more conventional manufacturing processes are used, DFM can conflict with design optimization, not always allowing the optimized shapes (Gebisa & Lemu 2017). Additive manufacturing can overcome that conflict due to the possibility to create various geometries with advanced planning or post-treatment. However, there are certain limitations when the device under development will be manufactured. For example, 3D printers have limited volume of a part that can be printed. Additionally, assembly of the device will be performed by customers, hence construction should be simple and easy to assemble. These aspects will be covered by DFMA later in design stages.

1.3 Product Development

According to Ulrich and Eppinger (2016), product development is a set of activities that begins with perception of a market opportunity and ends with the production and sales of a product. Scope of the thesis is development of the product — an arm prosthesis. Following all necessary steps of a product development is the easiest way to ensure that the product under consideration will have a chance to be successful.

Ulricp and Eppinger (2016) describe extensive structure of product development processes, that can be applied to various products of different scale. For the thesis, author simplifies the structure, but keeps the most critical points. The structure is presented in Figure 7.

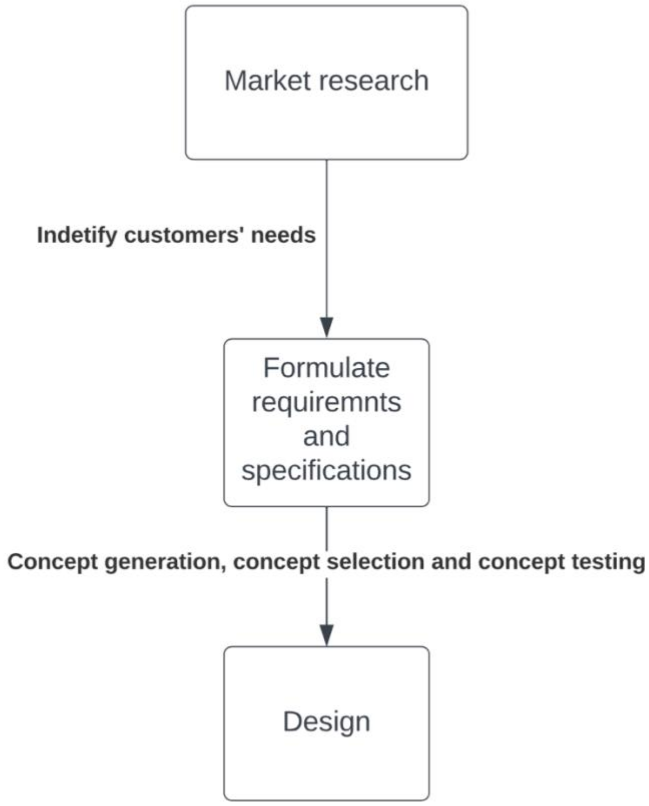

Figure 7. Product development for the thesis

1.3.1 Market research

The first step in developing a product is to identify who will be using the product. Nobody wants to spend resources on a product that will have no demand. The product to be developed during the thesis targets people with kids that cannot afford to spend thousands of dollars on prosthetics every year. Kids grow fast and new prosthetics for them are required often: every 8 to 14 months. Arm prostheses are expensive (Hawkins 2015); therefore, their regular replacement can become problematic for many families.

Prostheses are not only tools that replace a lost limb, but they also allow to socialize (do not stand out of the crowd). Hence the prosthetics appearance is important for customers. Huinink et al. (2016) name unattractive appearance among the main reasons for abandoning body-powered hand prostheses. Other reasons are pain and lack of comfort during the use and dissatisfaction with instructions and training received before acquiring a prosthesis. These factors will form a ground when formulating the needs.

1.3.2 Specifications

Customer needs do not express what exactly should be done but represent customers' desires in a vague form. To provide more exact, numerical requirements, engineers translate customer needs into product specifications. Ullman (2010) states that if a design team can formulate good requirements, then the team understand well what the problem is to be solved. Specification (often referred as requirements) should be expressed numerically, having a value and units that value has.

Ullman (2010) offers Quality Function Deployment (QFD) as one of the best and the most popular methods for generating requirements; however, QFD and House of Quality it offers are too complex for the thesis work. The process presented by Ulrich and Eppinger (2015) is structured, generic, and suitable for the planned product. One change to the process should be made: since the thesis is focused on customers, a lot of attention will be paid to interpreting their needs and using them for concept generation. It was decided that specifications can be developed after the concept will be finalized.

2 Product development

2.1 Mission statement

According to Ulrich and Eppinger (Ulrich & Eppinger 2016), mission statement formulates target market for the product, business goals of development team, key assumption, and constraints. The mission is to develop an affordable, below-elbow arm prosthetic for children that can be easily printed at home. The product is aimed to be non-profit, therefore, there is no need to develop business goals for it. The key assumption is that product will be usable for children of ages from 2 to 16 and it will cost significantly less than ordering new prosthetics. It is assumed that a family will be ready to invest into 3D printer, otherwise 3D printers can become the main constraint. Figure 8 presented structure for the product development.

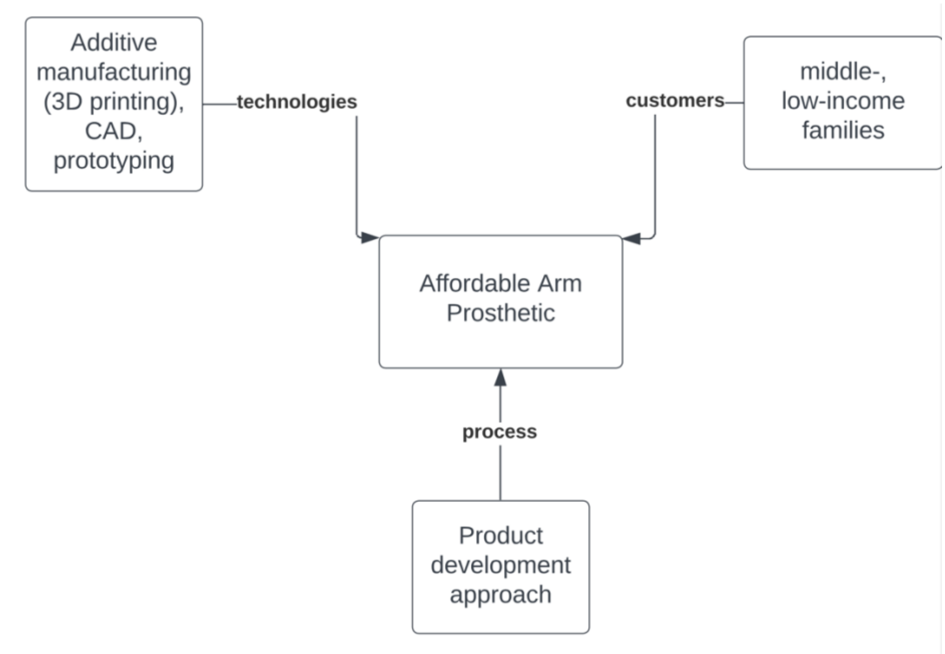

Figure 8. Three main parts of the product in development

2.2 Market research

The market of companies and startups that design and manufacture prosthetics is growing, as technologies of additive manufacturing and consumers electronics become more affordable. Open Bionics, company based in the UK, design and manufacture prostheses that have multiple types of grips. Their prosthetics are produced using additive manufacturing and utilize myoelectric sensors that read electromyography signals from muscles (Wikipedia 2022) and use them to control prehension. Figure 9 shows an example of Open Bionics product. One can notice that Open Bionics arms do not aim to resemble a real hand, but rather try to bring more individuality to its users. Diversity of paint jobs and designs can be seen in Figure 9. As for the price, it is not publicly disclosed, but reported to be at least a few thousand dollars (Hawkins 2015).

Figure 9. Different design of Open Bionics arms (Open Bionics 2022)

Unlimited Tomorrow, another company that develops advanced prosthetics, designed their artificial hands to have shape and colors similar to what a real human hand is. Figure 10 demonstrates skin tone selector for an arm on Unlimited Tomorrow website.

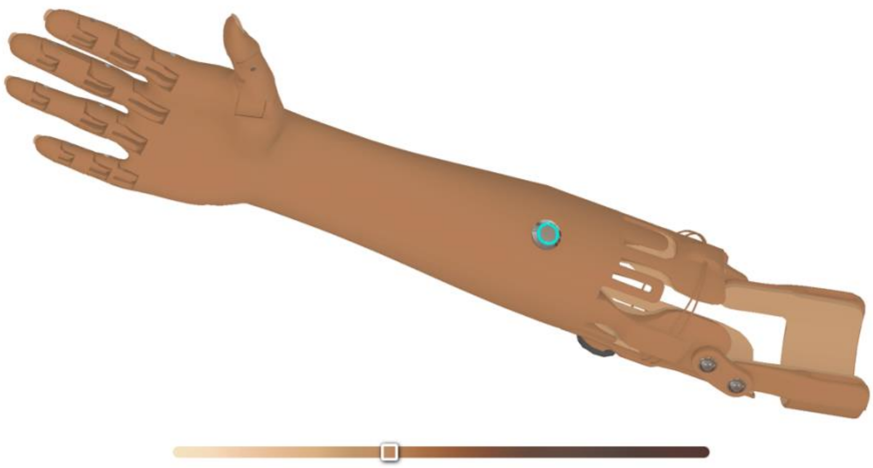

Figure 10. Skin tone selector (Unlimited Tomorrow 2022)

There is also a global community of people with 3D printers called e-NABLE. They use publicly available designs of prosthetics and a wide net of volunteers to print arm prostheses for people in need of one. Idea of the community overlaps with the thesis goal and their designs can be used as a reference or inspiration.

2.3 Identifying customer needs

The product under discussion should be heavily focused on customers. Therefore, identifying what is needed by customers should be helpful in building the product for maximum customer satisfaction. Customer needs do not reflect what will be developed in the end and identifying needs should be done notwithstanding how the needs will be fulfilled by engineers (Ulrich & Eppinger 2016).

Customers can rarely formulate what they want from their prosthetics. Therefore, it is job of engineers to observe users' behaviour and reflect on what customers need. The best persons to observe are so-called extreme users. Von Hippel (von Hippel 1988) defines extreme users as those who face needs that will become general for markets in a few years. However, studying extreme users for arm prosthetics is challenging, as all possible use cases have been explored up to date; shifting focus from extreme users to active users can be more beneficial because it will provide new perspectives on how current limitations of body-powered prosthetics can be overcome. Tilly Lockey, who is a tester for Open Bionics, can be considered as an active user. She shares her experience with bionic hands through her YouTube channel.

Cybathlon, a competition organized by ETH Zürich, aims to boost development of prosthetics industry. People with disabilities who use different assistive devices (including hand prostheses) compete against each other in completing daily tasks. A list of the daily tasks is available online and can be analyzed later.

To better understand how engineers in the industry work with customer needs, one can look at literature. Ulrich and Eppinger (2016) offer a five-steps method for customer needs identification. These five steps are:

1. Gather raw data from customers.
2. Interpret the raw data in terms of customer needs.
3. Organize needs into a hierarchy of needs.
4. Establish relative importance of needs.
5. Reflect on the results and the process

Due to limitations of the thesis project, these steps will be reorganized and presented in the list below:

1. Gather raw data from customers
2. Interpret the raw data in terms of customer needs
3. Reflect on the result and the process

Organizing the needs into a hierarchy can be omitted for two reasons. Firstly, the needs are gathered and interpreted by one person, therefore risk of formulating same needs is low, and elimination of repetitive needs does not require a separate step. Secondly, since the number of needs will not exceed 50, it is possible to work with initial list of needs.

Establishing the relative importance of the needs can be incorporated into interpretation of raw data. As mentioned in the previous paragraph, the interpretation will be performed by one person only.

2.3.1 Raw data from customers

There are multiple ways to collect data, such as interviewing customers or observing their behavior when using a product. Observing videos with children using prosthetics and reading and watching interviews with them was selected as the main method to gather data.

For example, Peregrine Hawthorn from Learn Liberty story (2016) admits that he sees himself as a cyborg. He also says that possibility to upgrade his arm is important for him and that modification allow Peregrine to become his own ideal. The young man also points out that a lot of effort goes into making hands work with the user. Peregrine reveals that most of his problems from an absent limb were social, as other children used to notice his difference from them. Peregrine and his father are also helping children's hospitals by printing hands for them, and their current project are hands styled like Spider-Man suit, bringing individuality to prosthetics and making kids feel special. Different custom prostheses are depicted in Figure 11.

Figure 11. Children in a hospital (Learn Liberty 2016)

Tilly Lockey is a girl who has been missing both of her hands since she was 15 months old. In one of her videos on YouTube (2021) she shares her experience of using prosthetics from age of 2. Tilly says that her first body-powered prosthesis that is shown in Figure 13 caused a lot of inconvenience, as the way they operated was visible and attracted a lot of undesirable attention. What is more, she thought of her first prosthesis more as a weapon, not as her arm.

Another thing worth paying attention to are grip modes. Movement of a thumb and opening and closing of palms are controlled through muscles, and initial position for thumbs can also be defined. Except usual grasping, Tilly can freeze her arm to hold objects that require constant prehension. Additionally, movements like pinching are available through locking movement for two or four fingers. Prehensions demonstrated in the video are seen in Figure

12. The girl often points out that making different gestures such as “like” or “peace” signs is a big advantage.

Figure 12. Different types of prehension of Tilly’s arm (Lockey 2021)

In Tilly’s other video, she talks about how she uses her prosthetics in everyday life. First, her bionic arms help Tilly to hold smaller object, like portable hairbrush. Secondly, she does not use her hands for typing on a computer or a smartphone, eating or opening packets. The reason is not explained; however, a conclusion can be drawn that agility of fingers of advanced prosthetics is not enough. Tilly also highlights that stationary palm complicates certain actions.

Figure 13. Tilly Lockey with her first prosthetic. Arrow depicts its operation (Lockey 2021)

Kristie Sita who has lost her left hand in an accident 7 years ago also shares how she does things differently as an amputee. Because Kristie is only missing a hand and most of her arm below elbow is there, she does not use her prosthesis to complete daily activities. There are several reasons that account for not using the prosthetics. First of them is inconvenience of prosthetics. Because Kristie lost her hand when she already was a grown-up person, she has been using her hand before a lot. After getting her body-powered prosthetic that was designed to replicate Kristie's hand, she has not been using it, as it did not look natural (the prosthesis made an amputated arm longer than the other one). Figure 14 clearly shows that Kristie prefers to use her mouth to hold a shoelace rather than use her artificial hand for the purpose. To tackle it, more degrees of freedom should be added, and overall convenience and simplicity of use can be improved. In mechanics, the number of degrees of freedom of an object represents the smallest value of real-numbered coordinates needed to define object's configuration (Lynch & Park 2017). Hence the bigger the number of degrees of freedom of prosthetics, the more movement it can provide to its user.

The second reason is lack of training for prosthetics. Huinink et al. (Huinink, Bouwsema, Plettenburg, van der Sluis & Bongers 2016) claim that training and preparations improved functional use of prosthetics and increased acceptance of prosthetics. Therefore, a good training material would be an important part of the product. Since the product under development targets children as its main customers, making them comfortable with prosthetics and teaching them how to use their prostheses in everyday tasks. Proper training is considered as one the success factors for medical devices, according to Tamsin and Bach (Tamsin & Bach 2014). Even though authors assume medical equipment and healthcare practitioners, the focus on teaching those who will use medical devices.

Figure 14. Kristie Sita using her mouth to tie shoelaces (Sita 2020)

Reviewing challenges from ETH Zürich Cybathlon, one can understand what is needed for prosthetics users. In competition description organizers highlight that modern prosthetics lack wrist agility and sensory feedback. They also emphasize importance of acceptance of a prosthesis.

2.3.2 Interpret the raw data in terms of customer needs

The prosthesis can have different colors and patterns
The prosthesis resembles a hand
The prosthesis is easy to fit
The device is operated naturally
Different prehension types are avaliable
Arm can freeze for longer prehension
The device allows agile palm movement

The prosthesis has attractive appearance
The prosthetic is affordable
The prosthetics is recyclables
The device can be modified
The device have training materials
The device provides feedback to its user
The prosthetic is comfortable to wear

Table 1. Customer needs

After analysing available material from open sources, needs displayed in Table 1 were formulated. The most discussed topic was appearance of prosthetics. It was generally agreed that artificial limbs that replicate appearance of real hands look unattractive. At the same time, it is important for prosthetics users, especially children, to have opportunity to modify prosthetics and express themselves through it. Tilly Lockey, for example, has changeable panels on her prosthetics. These panels have different colours and patterns. The design challenge here is to make prosthetics look attractive, but it should not drag unwanted attention at the same time.

Example of Kristie Sita demonstrate how important training is for prosthetics users. Training program or its development is not a topic related to engineering yet training materials can be included into final product package with proper rehabilitation training. Moreover, the prosthetic to be develop has children as target customers and helping them to adopt to their prosthetics is half of the product's success.

One of the most important and natural expectations from a prosthesis are its agility and adequate number of degrees of freedom. Human's fingers allow sophisticated and complex types of prehension. However, even the most advanced artificial arms struggle to provide separate control for each finger and enough degrees of freedom for the fingers. Users also seek ways to fix hand's position for longer period. Movement of a palm is also a restrictive factor.

Finally, price and affordability of a prosthesis are important for target customers. Children do grow fast and change of prosthetics is required more often than for adults. Potential trade off is lack of force to pull trusses of body-powered prosthetics by children.

2.4 Concept Generation

Usually at this step specifications are developed from customer needs. However, for the product under development it was decided to first develop concepts and select the final variant to be developed. Based on the selected concept the final specifications will be derived. In more traditional product development approaches specifications are first developed after customer needs are defined, then concepts are generated, and specifications are reviewed again, because each concept has its own limitation. Since resources and time are limited for the product under development, it was decided to perform concept generation and selection stages first and then define final specification based on a selected concept.

Concept solutions should provide means of tackling different functions that a product will have. Therefore, general function of the device under development should be defined first, then this function can be break down to smaller functions. To support these functions, solutions' sketches and textual descriptions will be used. Concept selection is then performed comparing suggested solutions for each function and forming an optimal concept from offered solutions. The expected result of concept generation is a wide range of different concepts, so no idea is overlooked. However, generation should be done in the shortest time possible, as the number of concept ideas will continue to grow (Liu, Bligh & Chakrabarti 2003).

2.4.1 Overall function definition

Overall function is a main function of a product. Defining it helps setting boundaries and creating a "black box" that has inputs and outputs (Ullman 2010). Diagram displaying the overall function for the product under development is shown in Figure 15.

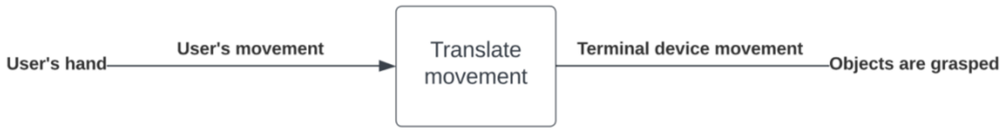

Figure 15. Top-level function of a hand prosthesis.

The function has an input — a user's hand, and an output — an object that is being grasped. Energy is also conserved within the function: user's movement is translated into terminal device movement. This function can now be decomposed to smaller functions that will be used for concept generation.

2.4.2 Subfunction decomposition

Subfunction decomposition leads to better understanding of the design problem and provides exact scope of problems for which concepts should create solutions for. The result of this step is presented as a diagram in Figure 16.

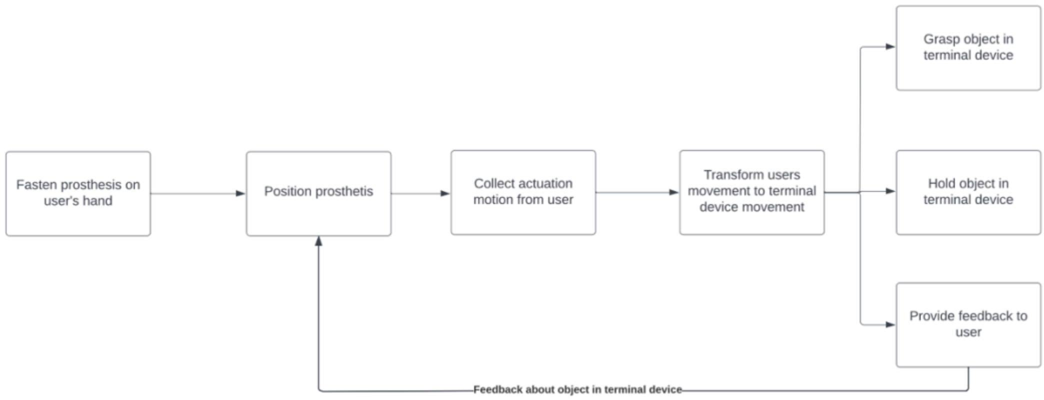

Figure 16. Overall function decomposition

With overall function being broken down to smaller subfunctions, it is easier to develop concepts, because subfunctions indicate what a prosthesis should perform, and it is designers' responsibility to decide how a concept will do.

Use of a prosthesis, as from Figure 16, starts with fixating the device on user's hand. Providing comfortable and convenient connection between an arm and a prosthetic is crucial for users, as seen from customer needs. Right positioning of prosthetics dictates how objects can be grasped and manipulated; active customers often complained that palm or terminal device movement is restricted which makes prosthetics users to perform unnatural movements. Comfortable interface will influence customer as much as prehension functions of prosthetics.

The next two steps are getting actuating motion from a user and transforming it to terminal device movement. As the product concepts are not finalized at this point, there is no defined way how these functions will be realized, but products that are already on the market use soft attachment to a shoulder that has a cable that connects the soft attachment and a prosthesis. Movement of the cable is then translated into movement of a terminal device.

The last three functions should be performed simultaneously, and these functions are responsible for holding the object, providing possible feedback, and keeping posture of artificial fingers or terminal device. While first three functions are obvious, the fourth function, keeping terminal device position, can be needed for social communications: taking pictures with friends or pointing at objects. This function originated from customers' need for interaction that is especially crucial for kids.

Before process of actual concept generation begins, one should be reminded that the prosthetic to be developed does not aim to be a tool nor substitute a real hand. The final product should provide new means of using prosthetics.

2.5 Concepts

Now the generated concepts, their implementation of functions (*how?*) will be reviewed. Each concept is presented in a form of sketch with small textual description in the picture which will be repeated and extended in the text.

2.5.1 Concept 1

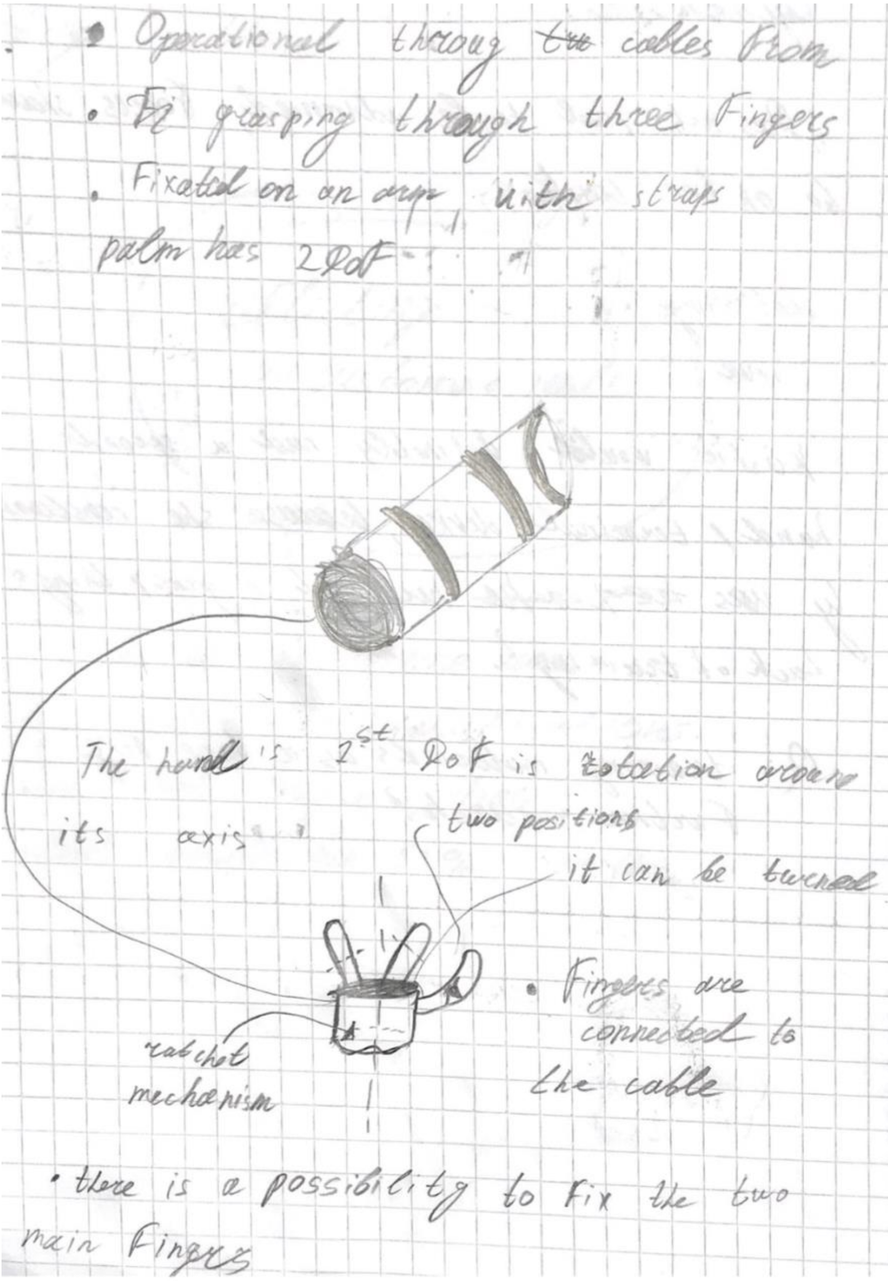

Figure 17. First generated concept

The first concept is rather conventional and has two main parts: socket that embeds a hand with two straps and a terminal device with two DOFs. The terminal device is actuated through a cable which is the most widespread solution for body-powered prosthetics. Because agility of a palm or terminal device was often mentioned when customer needs were being formulated, ratchet mechanism was offered as a solution. Customers have also asked for different fingers' positions: the concept assumes that each finger should retain its position after it has been manually oriented. Figure 17 shows sketches of the concept.

2.5.2 Concept 2

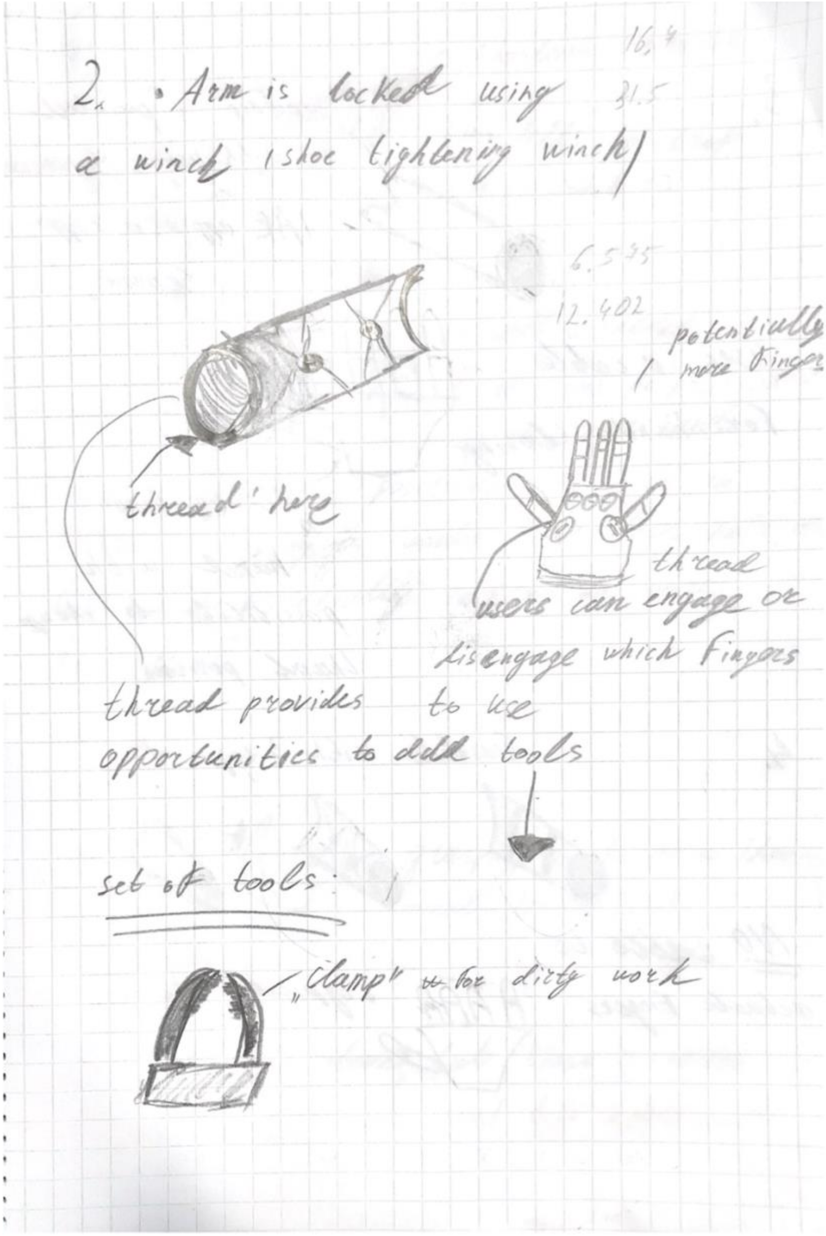

Figure 18. The second concept

The second concept also consists of two main parts, but the socket will use winches, similar to what is used in shoes as shown in Figure 19. The mechanism helps to tighten strings and release them quickly. The concept allows having different tools for different applications if needed. Figure 18 demonstrates threads on both the socket and the terminal device. The hand-like terminal device can have more “fingers” than a human hand. This decision opens more opportunities for prehension yet keeps more natural appearance of prosthetics.

Figure 19. A shoe with a winch (Arsutoria 2019)

2.5.3 Concept 3

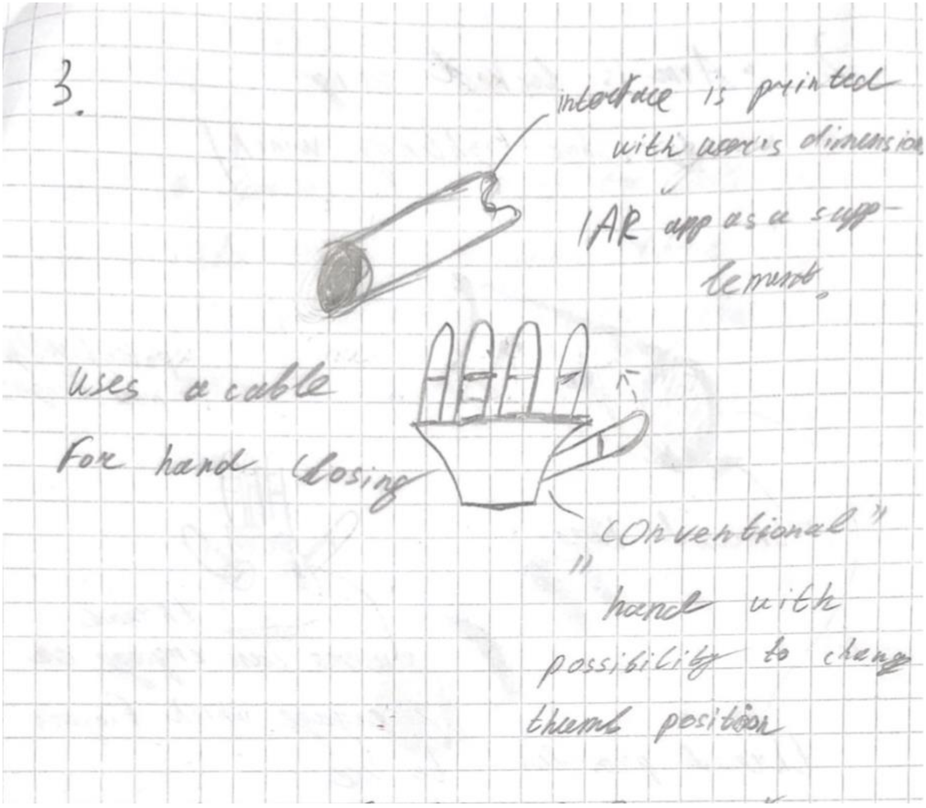

Figure 20. The third generated concept

The third concept, like two previous ones, consists of two main parts. The first noticeable distinction is socket design: it is meant to be printed and designed specifically for a customer. A mobile application that uses augmented reality features to scan user's hand and create socket of a shape that will fit customer the most. The terminal device is still actuated by a cable and has an option to position a thumb differently. The concept is a collection of the most general solutions. Rough sketch of the concept is shown in Figure 20.

2.5.4 Concept 4

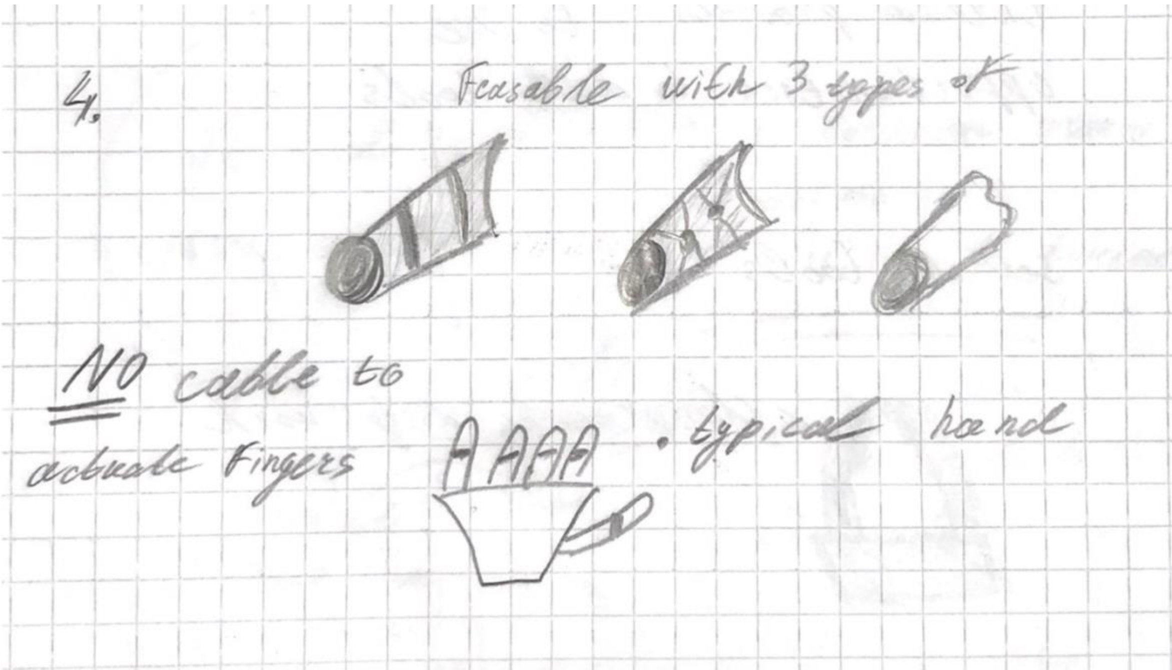

Figure 21. The fourth concept

The fourth concept's main idea is that it does not require a cable to be actuated. In theory, a user will set position of the terminal device with the other hand. The concept also offers different options for socket design. These options are a repetition of previously offered designs. Drawings in Figure 21 do not have many differences from previous sketches.

2.5.5 Concept 5

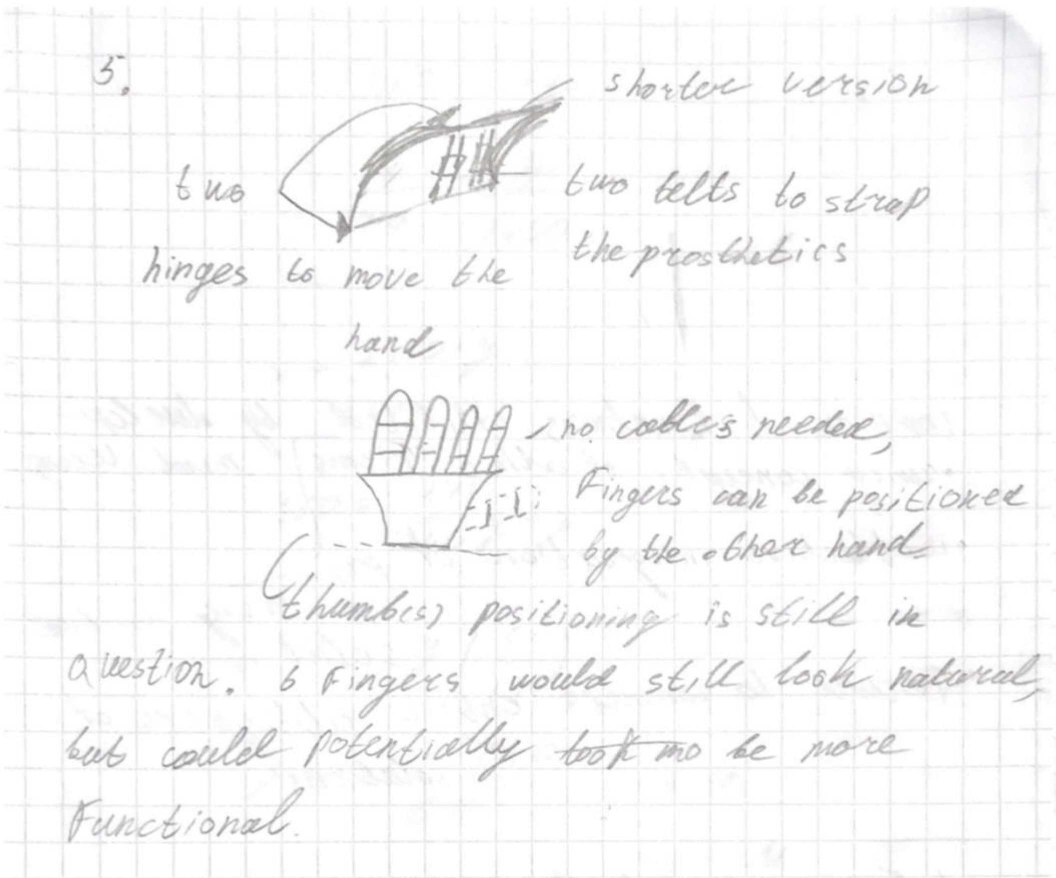

Figure 22. The fifth concept

The fifth concept offers same actuation option as the previous concept did: position of a terminal device is set with user’s other hand. However, the offered socket is shorter and will take approximately half of the length of previously shown sockets. As for the terminal device of the concept, it is a hand-like version, as shown in Figure 22. Number of fingers is undecided, because bigger or smaller number of fingers can affect prehension and comfort of use.

2.5.6 Concepts 6 & 7

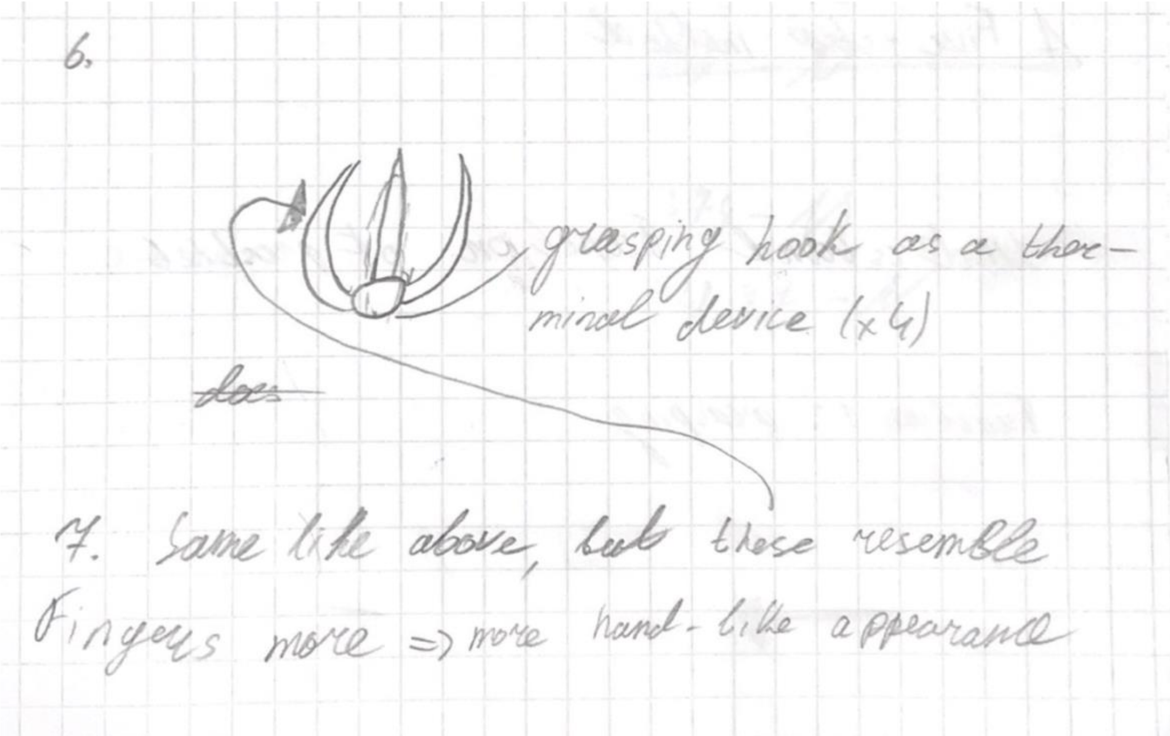

Figure 23. Concepts 6 and 7

Prostheses offered as concepts 6 and 7 do not provide any solution for a socket, assuming that it might be reused from previous concepts. Solutions for terminal devices are different and aim to provide more grip and better prehension, because they do not try replicate human's hand. The concept 7, as seen from notes in Figure 23, intends to blend a terminal device that looks like an octopus with appearance of a human's hand.

3 Concept selection

At the end of the previous chapter concept were generated and a short description of each concept was given. Solutions provided by the generated concepts have not been rated or judged, because concept generation requires open-mindedness, hence all possible solutions should be considered. The next step in the product development cycle will be comparing the solutions and finding the most optimal combination for the future product.

3.1 Concepts' solutions

The selection will be selected by putting functions of all concepts in a table, rating them using numerical criteria and combining the most successful solutions. Concepts broken down to functions are shown in the Table 2 below.

	Fasten prosthethis on user's hand	Position prosthethis	Collect actuation motion from user	Transofrm users movement to terminal device movement	Grasp object in terminal device	Hold object in terminal device	Provide feedback to user
Conept 1	Long connector AND 2 straps	Movement of a hand below elbow AND rotation with ratchet mechanism	Sleeve on the oposite shoulder	Cable from sleeve to terminal device	3 fingers in terminal device	Keeping the shoulder tensioned	Direct vibrations from device
Conept 2	Long connector AND winches	Movement of a hand below elbow AND rotation with thread	Sleeve on the oposite shoulder	Cable from sleeve to terminal device	Multiple fingers with 2 thumbs AND option to deactivate each finger	Keeping the shoulder tensioned	Direct vibrations from device
Conept 3	Tailored connector	Movement of a hand below elbow	Sleeve on the oposite shoulder	Cable from sleeve to terminal device	4 fingers for grasping (by cable) AND manually adjusted thumb	Keeping the shoulder tensioned	Direct vibrations from device
Conept 4	Long connector, general shape	Movement of a hand below elbow	User adjust terminal device position with the other hand	Terminal device retains the position	Grapsing with 5 fingers	Terminal deivce retains position	Direct vibrations from device

Conept 5	Short connector AND two straps	Movement of a hand below elbow	User adjust terminal device position with the other hand	Terminal device retains the position	Grapsing with 6 fingers	Terminal deivce retains position	Direct vibrations from device
Conept 6	No unique offered solution	Movement of a hand below elbow	User adjust terminal device position with the other hand	Terminal device retains the position	Octopus-like terminal device	Terminal deivce retains position	Direct vibrations from device
Concept 7	No unique offered solution	Movement of a hand below elbow	User adjust terminal device position with the other hand	Terminal device retains the position	Mix of an octupus and hand-like device	Terminal deivce retains position	Direct vibrations from device

Table 2. Concepts' functions breakdown

Examining the table, one can see that no new solutions were offered for feedback function (”Provide feedback to user”). Implementing sensory feedback will inevitably increase price and will require additional calibration. Potentially sensory feedback is not needed for children who are getting their first prosthetics. Solutions offered for grasping object in a terminal device are the most diverse among other functions’ realization offered by the generated concepts. How effective these solutions are and how they support product goals will be discussed later, but the reason for such a big number of offered solution can be because of importance of a terminal device.

For fastening a prosthesis on a hand 5 different solutions have been developed. Two last concepts have not had any specific design for a connector, therefore, if selected, they can be complemented by one of the other solutions. Agility of prosthetics and how it can be position has also been a significant issue for amputees. Positioning of a prosthesis is mostly done with a hand below elbow, but movement of a palm, as was mentioned in previous chapters, is a difference maker. Some of the concepts offered a solution for that area.

3.2 Rating the concepts

Functions of each concept were rated on a scale from 0 to 5, and the total score was summarized. The results are shown in Table 3 below. The total score, however, does not represent the best combination of solutions. Each solution will be manually reviewed against other options and the best ones will fitted to the overall best concept.

	Fasten prosthethis on user's hand	Position prosthethis	Collect actuation motion from user	Transofrm users movement to terminal device movement	Grasp object in terminal device	Hold object in terminal device	Provide feedback to user		
Conept 1	3	5	4	4	2	2	2	Total:	22
Conept 2	5	4	4	4	5	2	2	Total:	26
Conept 3	2	3	4	4	5	2	2	Total:	22
Conept 4	2	3	3	2	3	3	2	Total:	18
Conept 5	4	3	3	2	3	3	2	Total:	20
Conept 6	—	3	3	2	4	3	2	Total:	17
Concept 7	—	3	3	2	4	3	2	Total:	17

Table 3. Numerical comparison of the concepts

Table 3 clearly shows that Concepts 6 and 7 have the smallest number of points. This is due to absence of points for the first functions. Points-wise, the second concept is the most successful, as it got maximum points for two solutions and were better in the most cases compared other concepts. There are two functions where the second concept obviously lacks points: first, inability to hold an object for a long time without tensioning user’s shoulder. Second problem is feedback from a prosthetic.

Even though the solution for grasping is highly rated, Concept 7 solution seems the most effective. It stills satisfies users’ request for natural appearance but provide significantly more usability than designs of “convenient” hand. To tackle the issue of retaining of prosthetic position, a mechanism that closes and open terminal device by being actuated can be implemented. Finally, motion of a palm realized by making a thread might not be the best solution, as printed threads might not be accurate enough; hence, adopting a ratchet mechanism can be an optimal solution.

3.3 Selected concept

After reviewing, rating, and combining all offered solution, the concept presented in Table 4 was selected as the most promising. It will be developed in the next chapter and a 3D model of it will be used as a prototype to either prove its success or failure. In addition to the model, specifications will be presented.

	Fasten prosthethis on user's hand	Position prosthethis	Collect actuation motion from user	Transofrm users movement to terminal device movement	Grasp object in terminal device	Hold object in terminal device	Provide feedback to user
Selected concept	Long connector AND winches	Movement of a hand below elbow AND rotation with ratchet mechanism	Sleeve on the oposite shoulder	Terminal device retains the position	Mix of an octupus and hand-like device	Terminal deivce retains position	Direct vibrations from device

Table 4. Final concept functional decomposition

4 Concept design

As the final concept was selected in the previous chapter, design of a prototype for a concept is described in this chapter. A CAD model created with SOLIDWORKS software will be used as a prototype. Such a prototype should be sufficient to rate the mechanics of offered solutions, the concept's manufacturability, and how viable the concept is in general.

4.1 Connector's design

The connector or socket was designed according to solution offered by the selected concept. First, the socket is half-open, which allows to easily fit a hand in. Then, according to the concept, a hand should be fixated using strings and winches. Sides of the socket are equipped with small connectors through which strings should go. It is possible that those strings tightened by winches will cause discomfort to users. To avoid the problem, a soft and elastic tissue can be worn between an arm and the connector. Finally, an end of the connector is equipped with two pivots for a base of a terminal device. 3D model of the connector is shown in Figure 24.

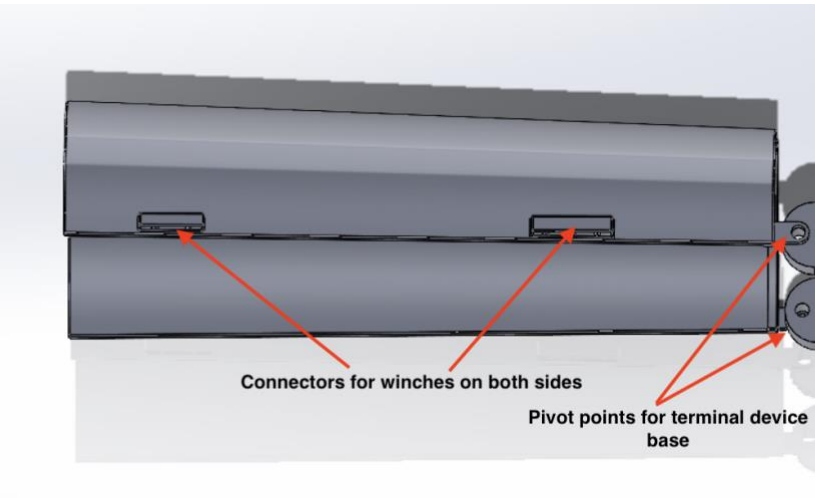

Figure 24. Connector 3D model

4.2 Terminal device design

Terminal device consists of two subassemblies: the first is a base of the terminal device where ratchet mechanism is placed, and the second part is the terminal device itself that performs prehension. Terminal device base allows connection of the terminal device to the socket and ensures rotation in one direction. The terminal device has the biggest challenge in terms of design, as it contains prehension functionality. According to the selected concept, the terminal device should retain its closed or open position after it was actuated. This idea is the biggest challenge for the concept because a mechanism that will perform the desired operation should be compact, printable, and possible to assemble by users or their parents. The Geneva mechanism was chosen to perform the task. The design of the terminal device is presented in Figure 25. The real implementation and user experience may vary from what is offered by the presented concept.

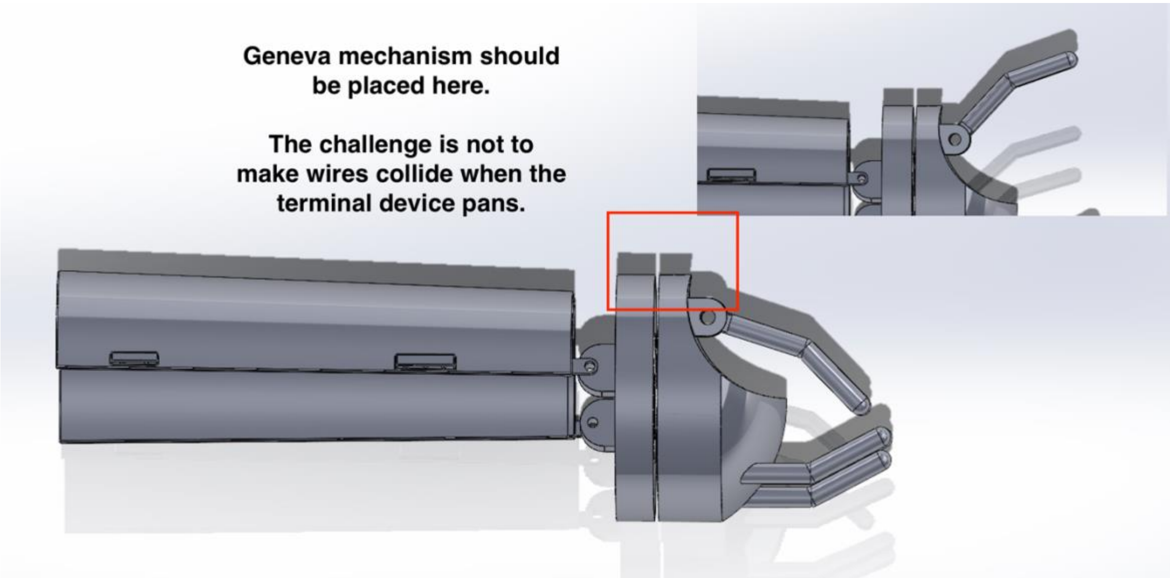

Figure 25. Terminal device and its operating principle

Talking about the terminal device's appearance, the developed model slightly resembles a human’s palm, but utilizes different principles for actuation, and, therefore, should be more effective in use. The way artificial fingers are attached to the terminal device can be seen in Figure 26. This way of attachment allows users to create fingers of their own designs for fingers with universal attachment point. As was studied from customer needs, prosthetics that fully replicate a hand’s appearance tend to have poor functionality.

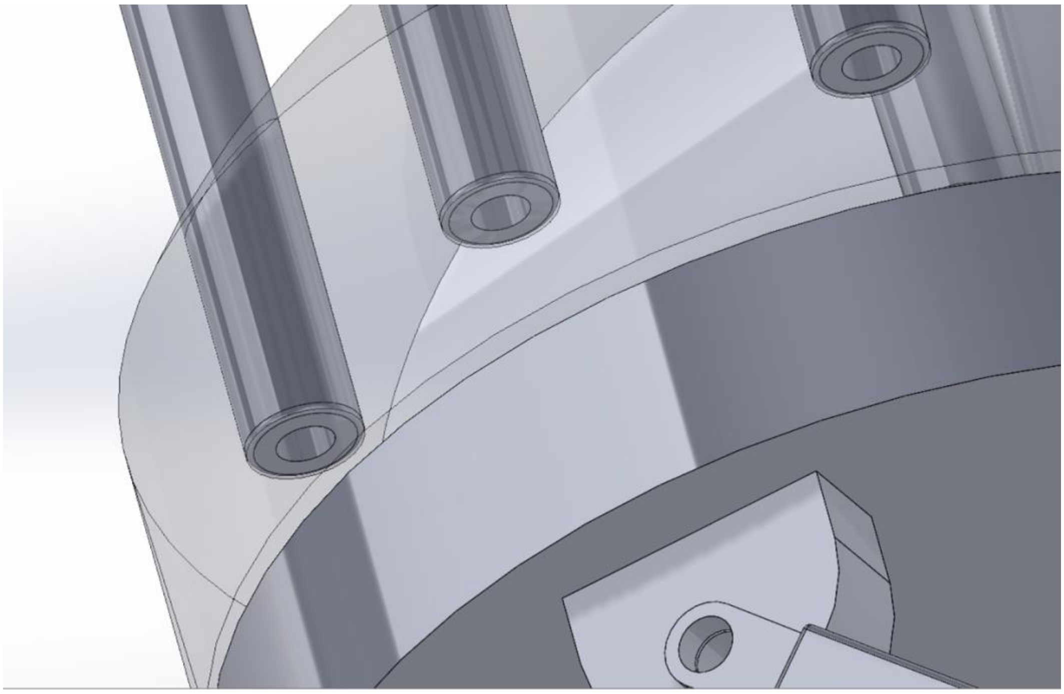

Figure 26. Pin attachment of artificial fingers to the terminal device

4.3 Material selection

Since the developed prosthetic will not be used inside human's body, requirements for the material are less strict than to the most medical devices. However, the material still needs to be flexible to some extent, durable and strong. Because the prosthetic is assumed to be 3D printed using hobbyists' printers, the number of available materials is limited and was presented in section 1.2.2.

PETG will be the best choice for the prosthetic for several reasons. First, it is a food-safe material, which is especially important for kids. Secondly, PETG has high temperature resistant. Finally, the material can bear high impacts (Slump 2021). The material should be good enough for every part in the assembly.

The second favorite option is PLA Plus. The material is an enhanced version of regular PLA. The improved characteristics are achieved by different additives. The major drawback is, however, relatively low melting temperature of the material (Fuentes 2021). It is worth noticing that characteristics will also vary from different filament manufacturers.

4.4 DFMA

Two important DFMA aspects were considered when designing the prototype. The first aspect is the ease of assembly because the device is assumed to be assembled by its users or parents. The prototype was designed to be assembled in one direction to ensure that this aspect is achieved. The fully assembled device is shown in Figure 27, while the exploded view of the assembly is displayed in Figure 28. Only pins for pivot points will be inserted perpendicularly to the main assembly direction.

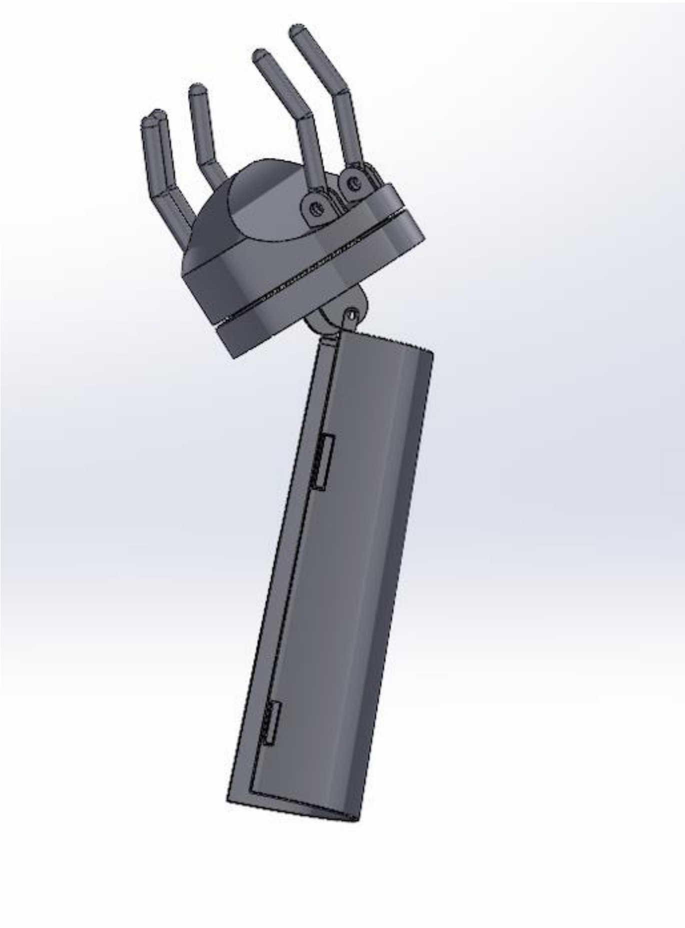

Figure 27. The assembled device

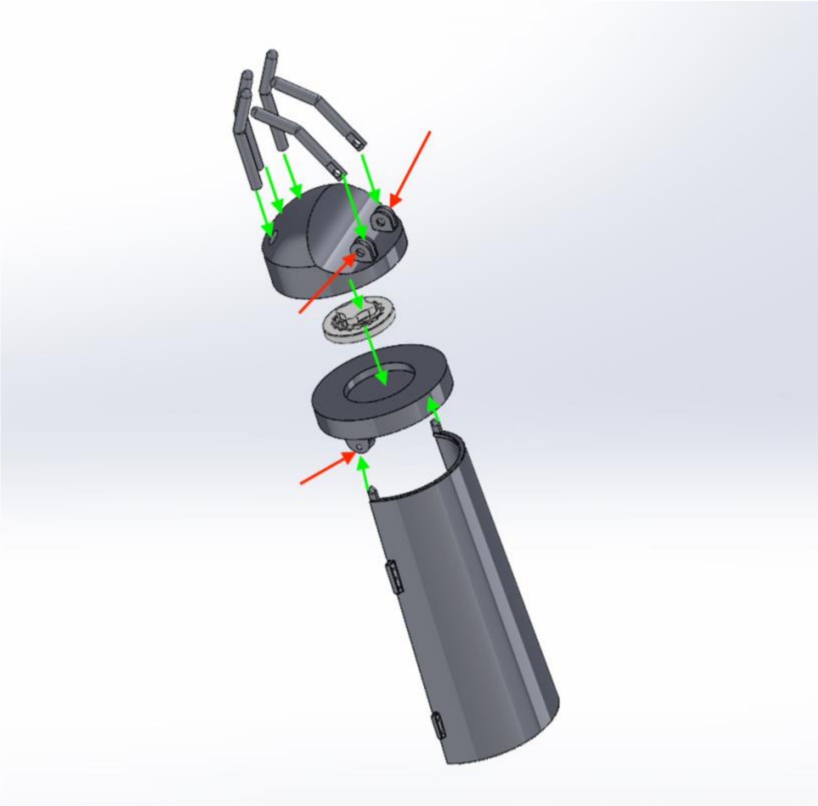

Figure 28. Concept’s directions of assembly

The other aspect was scalability, as the device should “grow” with its user. Design tables and dimensions defined by equations were used to create different sizes. The use of equations is shown in Figure 29. The problem with the concept is that there is no easy way to interact between an end-user and the concept to adjust sizes. Access to the source model can be granted, but another interface would be more convenient. The ratchet mechanism is designed by Buck Baskin (2017).

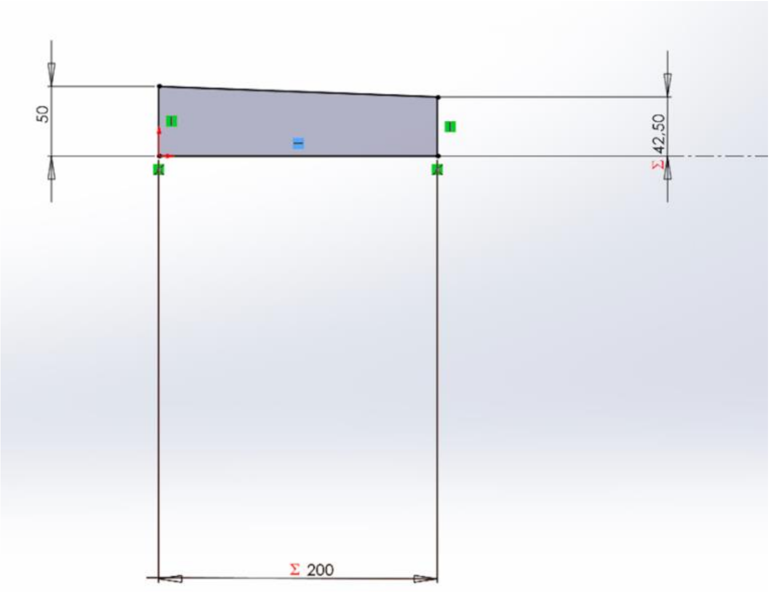

Figure 29. Equations used for the connector design

4.5 Costs

According to Prusa website (Prusa Research 2022), Prusa i3 MK3S+ printer costs 999 Euro. The biggest version of the prosthetic assembly weights 0.62 kg. Available Prusa filaments for their printer cost 29.99 Euro. The final costs of the concept are presented in Table 5.

	Printer	Filamet	Total (Euro):
Costs	999	29.99	**1028.99**

Table 5. Costs of the product

Considering that printer is a one-time investment, and a roll of filament can be used for two prosthetics, the concept is affordable.

5 Conclusion

The thesis was developed with the aim to create a concept of an affordable below-elbow prosthetic for kids. Using the right product development practices should have helped to achieve the desired result. However, certain challenges occurred.

First, the thesis work was carried out by one person. Ideally, an engineering project should be done in a group. Doing the same work in a team will at least bring more diversity to concept generation and will make design development more effective. Finally, teamwork allows sharing of engineering expertise and supports learning and professional growth.

The product development approach used in the thesis work was a combination of what is used in the industry and described by some authors. It is close to standard product development approaches, but it is still worth checking it in the real-life application with the product going further than the concept stage. The modified approach did work well for the developed concept in theory, but no physical actions were taken to try the concept out. Implementing the concept as a printed model can highlight some drawbacks or flaws.

The created 3D model has demonstrated the ideas proposed by the selected concept. However, a more detailed version is needed if there is an intention to continue with the concept as a product. For example, the closing and opening mechanism for the terminal device is not implemented in the 3D model. Therefore, the concept is either not the best choice for the final product or requires more detailed development to add the Geneva mechanism.

Finally, the author discovered and studied multiple aspects that are not directly related to engineering but have a big influence on prosthetics as a product. The most important aspect is the availability of teaching and training materials for prosthetic users. It was pointed out by different researchers that understanding how a user can operate his or her prosthetic improves satisfaction with the prosthetic and enhances user’s performance when using the prosthetic.

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