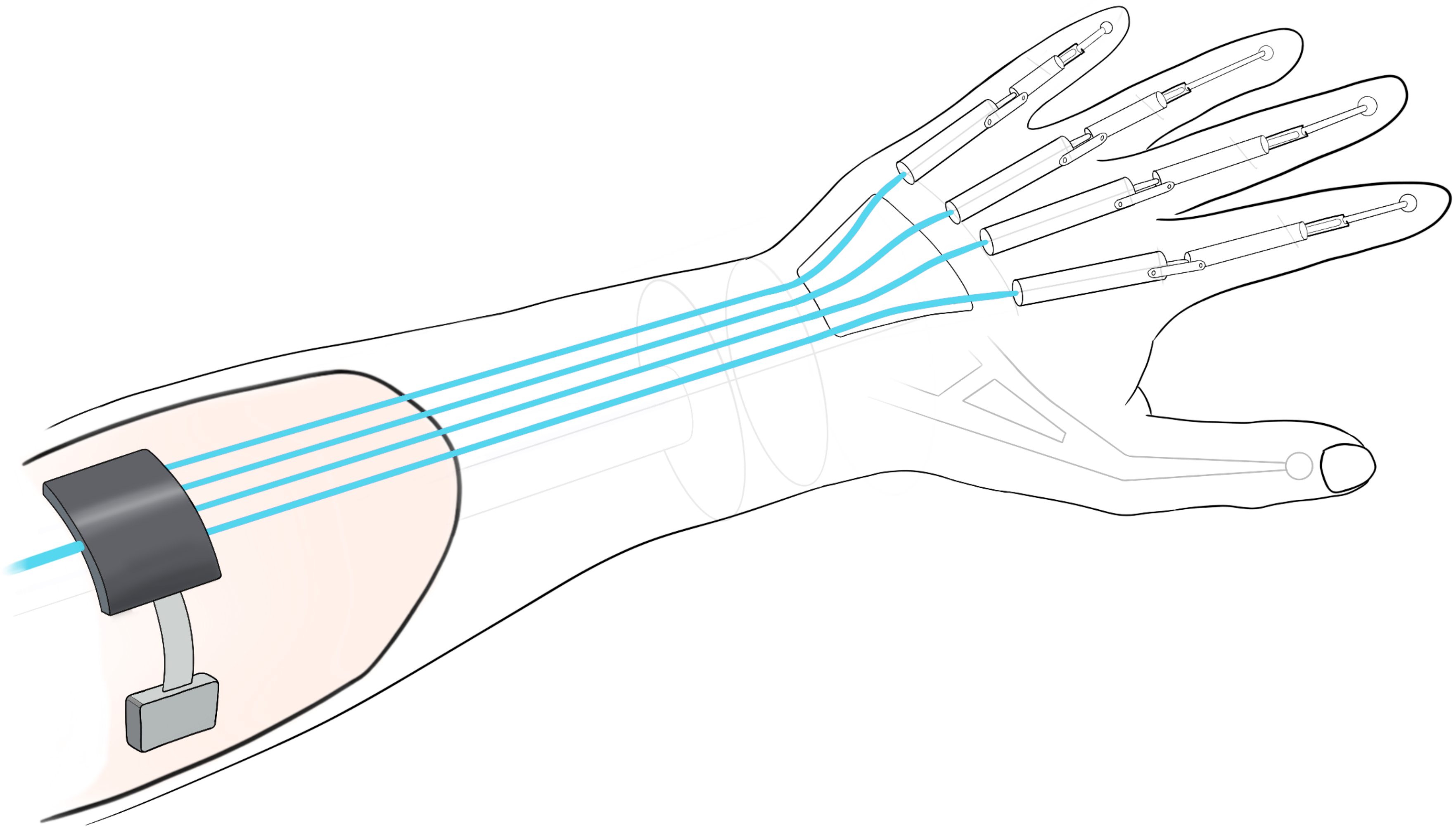

Eindhoven Cylinder Hand

A multifunctional Lightweight prosthesis with an optimal user experience.

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Abstract

This report describes and represents the design process of the Eindhoven Cylinder Hand, a hand prosthesis which is focused on being lightweight, while maintaining functionality to do various daily tasks and which is easy to use. These aspects combined result in the optimal user experience in terms of comfort and interaction.

The design process which resulted in this prosthesis has involved various stakeholders such as prosthesis builders, prosthesis manufacturers and of course end users. The main focus of this prosthesis was weight reduction, which proved to be the most problematic aspect of arm prosthetics, yet the added functionality has been maintained compared to alternatives on the market.

The Eindhoven Cylinder Hand is based on the Delft Cylinder Hand, which has been developed at the university of technology Delft in 2015. The Delft Cylinder Hand is a revolutionary prosthesis due to its innovative approach. The Delft Cylinder Hand is body powered and makes use of hydraulic cylinders, resulting in a lightweight design and a less incriminating interaction than traditional body powered prosthesis. However, the Delft Cylinder Hand could only open and close fully. The Eindhoven Cylinder Hand makes use of the strengths of the Delft Cylinder hand but adds more functionality to it by enabling various grasping methods. The concept was reviewed by experts and the results are promising.

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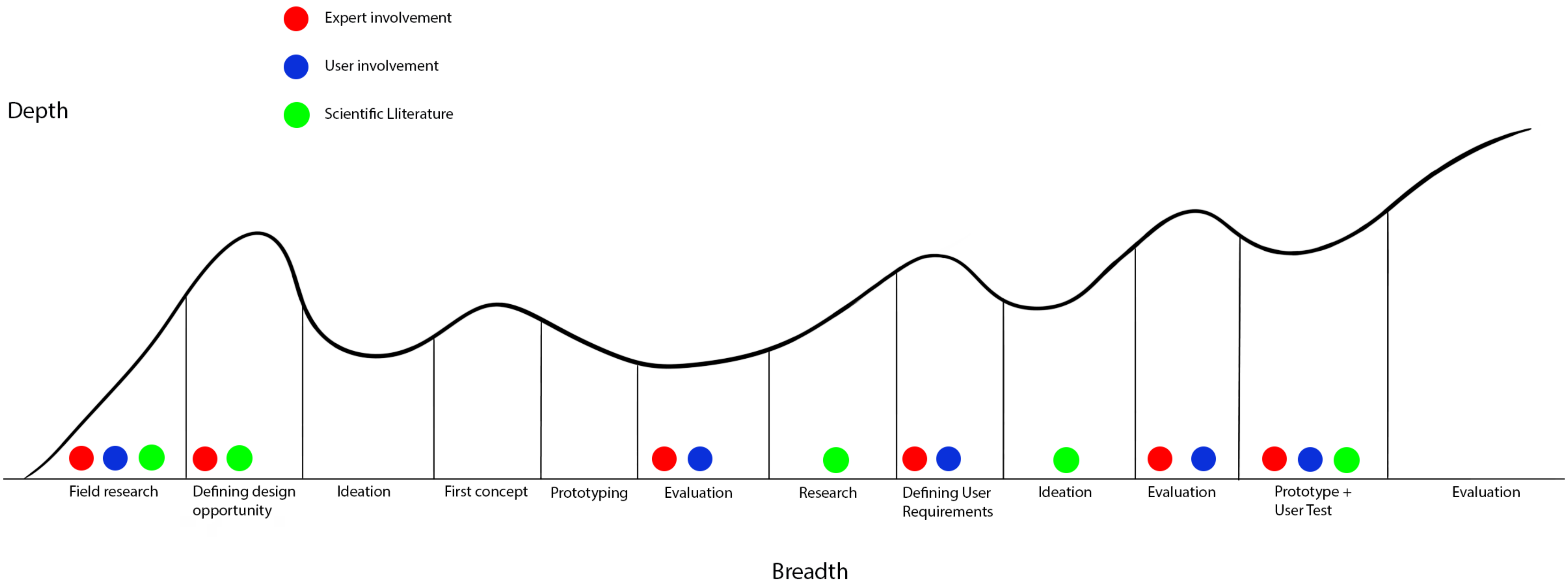

Expert involvement
User involvement
Scientific Lliterature
Depth
Field research
Defining design opportunity
Ideation
First concept
Prototyping
Evaluation
Research
Defining User Requirements
Ideation
Evaluation
Prototype + User Test
Evaluation
Breadth

Motivation

Our society is constantly changing at an increasing paste as various technological fields are flourishing. As designers we have the responsibility to implement these technological advancements in a way so that it benefits society as a whole. In the past 3 years I have explored various fields in which I contributed to this societal development through design, and gained insights in who I am as a designer and in what ways I want to contribute in the future.

After having done several projects in different areas I developed a curiosity for the health care sector. The design and research projects I have done in the sleep squad contributed a lot to this development and insight. Although those projects were mainly focused around behavioral change, I was intrigued by their influence on the wellbeing of individuals, which I assumed would also be the case in the health squad.
Furthermore I also interested in working more closely with different stakeholders, such as experts and end users, which would definitely help me with my personal development as a designer. The goals I set for myself in my personal development plan and the possibilities the health squad offered to realize my goals excited me to start with the project. I chose to do a project focused on prosthesis, as they have fascinated me for a long time. It is fascinating to me that we can build so many things with our hands, but that the best prosthetics are nowhere near as functional as a real hand. Besides that I am also convinced that a good hand prosthesis can add value to a person's live which little other tools/products can.

Vision

I believe that as various technological fields are flourishing, design will play an increasingly larger role in the implications of these new technologies. Due to those these developments, new designs will have a major impact on the world and society we are creating and the designers carry a great responsibility. Design can play a major role in the healthcare sector, may it be for physical rehabilitation or social and mental health. The workload is increasing on every level in the healthcare sector, negatively influencing both the quantity and quality of the treatments. I believe design can contribute to a solution for this growing problem in the healthcare sector. By integrating new technologies in interactive products we as industrial designers can improve the quality of help provided by medical experts and the user experience of the patient.

Besides improving the relation between therapists and patients, design can also play a large role in the self-empowerment of patients. By creating innovative and meaningful products, patients can regain autonomy in their daily lives. By doing so design can create a world of difference in the experience of the patients.

The insights I have gained during my final bachelors project are implacable in a broader range of fields than just in the healthcare sector. I am convinced that by integrating the expert knowledge and user insights, society as a whole can be greatly influenced by design, resulting in a better and more positive world.

1. Introduction

Behind every person with a prosthesis there is a story. Some people use prostheses because of congenital anomalies, others lost one or more limbs during their lifetime. Amputations are often the result of a traumatizing event in the amputees life. After the initial healing there lies a big road ahead in which the amputee will have to learn how to live without a hand, or without a leg. The simplest tasks become very challenging, and persons that used to be able to care for themselves need a lot of help overnight. This can have a major influence on their lifestyles, job opportunities, family structures and self-images. Amputees will also, just as people without a limb due to congenital anomalies, be confronted with social acceptance issues. Especially in childhood this can result in being picked on and feelings of incomprehension, with all the negative repercussions as a consequence.

As I designer I wanted to try to help people who need it the most. Technology for entertainment purposes or to enhance an already comfortable life are nice, but I would rather focus on people that don't have the privilege of living their lives in a normal and easy way. For my high school end project I developed a prosthetic hand based on a universal jamming gripper. Although the real life implication of it was not very promising, it was a critical moment in the development of my identity and vision as a designer. I realized that combining theory and practice was something that I could challenge myself with and I really enjoyed this process. During this project I also got involved with amputees themselves. I was shocked by how the prosthetics worked; some of them were electric and multi-functional but they cost a fortune, others just used a simple hook. It felt like technology just abandoned them. This where my fascination for prostheses started. Since then, many others like *Enable the Future* and Easton LaChappelle from *Unlimited Tomorrow* have been busy to try to innovate in the world of prosthetics, by making them more accessible and affordable. These initiatives really drive me as a designer, and give me hope for the future.

A prosthesis designed to integrate the insights and preferences of users can add so much value to a person's live, incomparable with most other enhancements of the quality of life we can provide as designers. During my design process I learned that various aspects of the needs from users are still not met in modern prosthetics. Throughout the process various stakeholders, such as end users, manufacturers and experts, were involved in the design choices of the project. Through this close relation with all stakeholders the focus of this project was formed. Literature and interviews with users and experts showed that weight reduction should be the number one priority in prosthetic design. Doing so is hard without compromising for both cosmetic and functional value. In this report I will further elaborate the design process from the start of exploring the field, to literature research, market research, user interviews and expert opinion. The project direction was developed based on the gained knowledge.

2. Context & Design challenge

In this chapter I will describe the process which led to the initial concept of the Eindhoven Cylinder Hand. Here I will elaborate on the process of gathering information on the topic and discuss various project directions that have been considered before selecting the definitive concept. During this process various stakeholders (manufacturers, experts and end users) were involved. By involving these groups of people I gained a much broader perspective on the subject than I could have ever done on my own.
Even though technologies are advancing, prosthesis users still experience various problems on either a day to day basis or in certain points in their lives. I initiated my field research by looking in depth at existing prosthetics and consulting scientific literature. The existing prostheses can be divided into three groups: cosmetic prostheses, body powered prostheses (BP) and myoelectric prostheses.

Existing Prostheses

The cosmetic prostheses are only focused on one aspect of the whole device, and very sophisticated at doing so. However, all functionality in terms of manipulating objects is neglected. A very select few people make use of these devices, as most people that wear a prosthesis strive to regain some functionality by using their device.
Body powered prostheses are traditionally available in two variants; the hook and the body powered hand. A cable is attached to both the terminal device (the hand) and a fitting around the users shoulders. By moving the shoulders away and towards each other the terminal device can be opened and closed. An advantage over more complex myoelectric devices is that these body powered devices give proprioceptive feedback: the user can feel how much force is applied to the grasped object. The body powered hook is very much focused on functionality. It is very light compared to other devices and easy to operate, however its cosmetic value is excluded. The body powered hand works identical but includes a silicone glove, imitating a natural hand. A negative side effect of this is that the prosthesis costs more energy to operate and due to that fact the prosthetic hook remains a popular choice to this day.

Myoelectric prosthesis make use of EMG sensors that measures muscle activity in the part of the arm that is still present. Based on these inputs the hand will either open or close. Multi-functional myoelectric prostheses are also available, that can perform various grasping maneuvers based on different input patterns of the sensors. However, these more advanced types of myoelectric prosthesis are harder to control and require a period of training. Besides that they are also extremely expensive, easily costing tens of thousands of euros. When people's insurance companies do not cover these devices, people often do not have any option to finance the device. Reducing the price in one way or another could be a potential design challenge.
After researching these existing prostheses I went on to read scientific literature to gain a better understanding of their properties. Out of this it became clear that current scientific evidence is insufficient to conclude that either system provides a significant general advantage (Cary et. al., 2015). This was initially strange to me, as the multifunctional myoelectric prostheses seemed far more functional and technologically advanced. However when doing further research it became clear why myoelectric prosthesis do not significant general advantage over body powered prostheses. Body-powered prostheses have been shown to have advantages in durability, training time, frequency of adjustment, maintenance, and proprioceptive feedback (Carey et.al., 2015). These facts compensate the lesser added functionality in comparison with myoelectric prostheses for a large quantity of people. Besides this, body powered prostheses also weight a significant amount less than their myoelectric counter parts. When researching body powered prostheses I discovered that there were no significant improvements in these devices compared with the data from 1987 (Smit et. Al., 2012). This was remarkable in my opinion, and seemed to be a promising lead in terms of design opportunities.

New technologies
Besides taking a scrutinizing look at the already existing prostheses I also looked into new technologies that might be applicable in the field, such as the advancement of soft robotics and the universal jamming gripper. Furthermore I looked into service based models to equip young children with myoelectric prostheses, as they grow out of them very fast which makes it unaffordable as they are provided right now. I also looked into new materials that could be used for the cosmetic gloves, as they still tend to tear/wear off quite often. These innovative approaches were useful to consider, but when doing more and deeper literature research a more essential problem was found, and these ideas just mentioned were discarded.

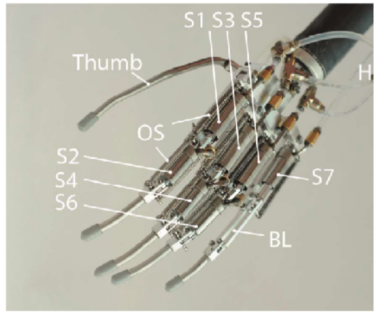
Prosthesis weight
The more central problem was prosthesis weight. During this stage of the project I was still working hard to come in contact with both user and experts. Via the internet forum Reddit I managed to come in contact with a prosthetist, who stated that the most requested enhancement by prosthesis users was weight reduction of their device. Consequently I proceeded by doing more literature research on this topic and found literature which really astounded me. Nearly 1/3 of prosthetic users is dissatisfied with the comfort of their device (Pezzin et. al., 2004). The more decisive factors in this perceived lack of comfort are the fitting and weight of the prosthesis. Due to the high weights of prosthetic hands, up to 30% of amputees do not actively use a prothesis (Smit et. al., 2015). It was clear that the high weight of a prosthesis were a problem but these rejection rates seemed abnormally high to me but other literature confirmed these statements. Eventually I even found a paper which stated that reduced prosthesis weight emerged as the highest priority design concern of consumers (Biddiss et. al., 2007).
In the meantime I managed to speak to a person with a congenital malformation. The person did not actively wear a prosthesis, making it a even more interesting subject. I set up a meeting and had a very interesting conversation. At the beginning of the meeting a questionnaire was conducted to gain insight in the reasons why the person did not use a prosthesis, and to gain insights in user needs. After the questionnaire an open conversation followed, in order to gain a broad and unlimited perspective on the topic.

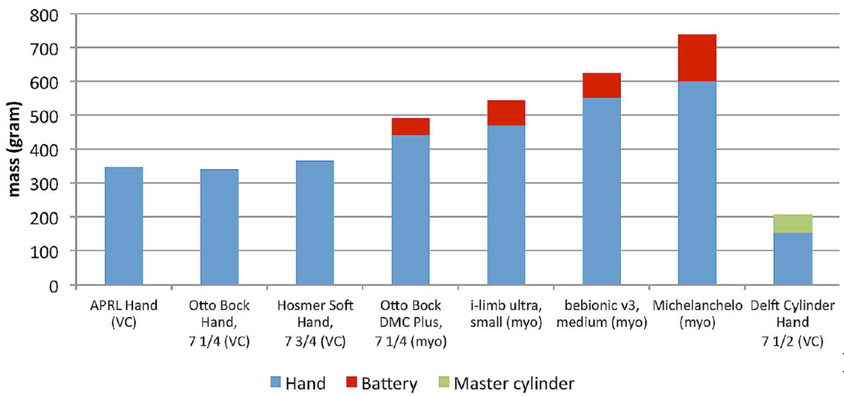
In order to validate my findings I applied theory from “Real world research: a resource for social scientists and practitioner-researchers” (Robson, 2002), in this case I used a method called member checking. This theory suggests that it is useful to discuss your interpretation of qualitative data and the conclusions that were drawn. With the questionnaire I tried to find out if prosthesis weight was the most major problem for this person too, and wanted to investigate into which compensation could possibly be made to reduce the weight.
As I spoke to the person and analyzed the questionnaire using Robson’s methods (Robson, 2002) it became clear to me that it not only the prosthesis weight, but that there should be a good balance between various factors. These factors include comfort of the device, added functionality and the ease of use. The reason being: if a prosthesis is very lightweight but still does not add any functionality, then it is still not worth it to wear the device the whole day through. Similar reasons arose for different imbalances in these factors. This sounded very logical but it was an new angle to look at the project, as I was a bit drowned in information from literature and did not see the bigger picture or connect all the dots.
Other information sources supported this viewpoint. One meta-analysis stated that users often cite that the functional advantage or cosmesis did not outweigh the discomfort or inconvenience of the device (Cary et. al., 2015). This discomfort of a result of the weight and fitting of the device. Limited function of prostheses may also cause awkward aberrant movements not normally experienced by persons without amputations, called compensatory motion (Highsmith et. al., 2008) which can result in various problem in the user’s posture. Limited functionality of a prosthesis can also lead to the overloading of the healthy limb which is of course undesirable.

When researching weight reduction of protheses, an innovative approach of a body powered prosthesis crossed my path. It was developed at the TU Delft in 2015, and it made use of hydraulic cylinders. Its name was the Delft Cylinder Hand (DCH). It was focused on weight reduction, and it achieved an incredibly low weight compared to all other devices. It was operated by manipulating a master cylinder attached to shoulder harness. When a force was applied by using the shoulders, water would flow from the master cylinder into the cylinders in the fingers, resulting in the closing of the hand.
It was definitely an improvement of the traditional body powered hook. Although the hand can only be opened and closed by operating the master cylinder, very similar to an traditional body powered hand, it has some significant advantages. The main difference is that with the DCH the user operates a cylinder instead of a cable, but the interaction in the same. It also shares the advantage of proprioceptive feedback with the traditional body powered prosthesis, opposed to myoelectric devices. Due to the implication of hydraulics the cylinder prosthesis is lighter and requires less actuation force than the traditional body powered hand. Despite these advantages over the traditional body powered prosthesis its functionality remains very limited, as it can only be fully opened and closed. However, its weight is almost half that of a traditional body powered prosthesis.

I was very intrigued by this innovative approach in the field of prosthetics, and was quite surprised that this innovation was Developed at the technical university of Delft. I reached out to the creator, Gerwin Smit, and managed to set up a meeting with him. I have seen and used the prosthesis myself and we talked about his views on the field of prosthetics. He stated that manufacturers try to push myoelectric devices, while neglecting the possibilities of body powered ones and he suggested me to look into a patent from D.W. Dorrance from 1912 in which the traditional body powered prosthesis was first described. We also discussed why de DCH did not come on the market. This was due to various reason, problems regarding insurance, the small market and complexity of the design. I wanted to look into ways of evolving this technology by tackling those problems for example. In order to do so I set up a meeting with a well-known company in the world of prosthetics called Össur.

Gerwin Smit and the Delft Cylinder Hand





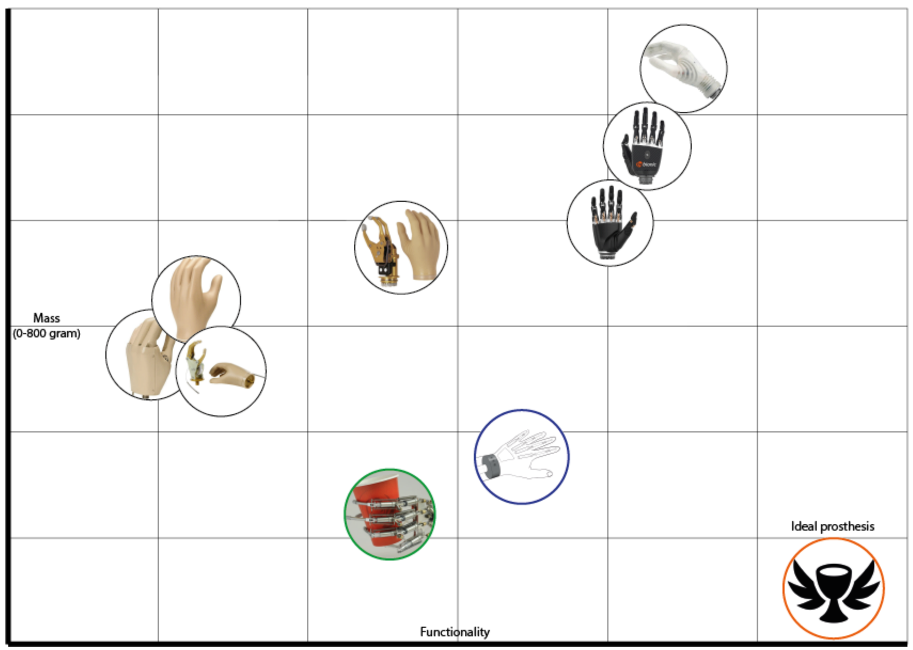
In 2016 Össur acquired the company Touch Bionics, creator of the famous myoelectric i-limb, a high end multi-functional myoelectric prosthesis. At this stage of the project, I had only been able to talk to Gerwin Smit and one person who missed a hand (since birth), so talking to someone with much experience in the world of prostheses was very valuable. I prepared a presentation with my findings thus far, proposing that weight reduction came forward as the most important factor prosthesis design in scientific literature. I wanted to discuss how this could be implemented in a real product and also wanted to know their opinion on approach like the Delft Cylinder Hand. The person that I spoke with, Peter Slijkhuis, stated that they were indeed continuously working towards a more lightweight version of their product. He was familiar with the Delft Cylinder hand, but was a fan in particular. He stated that the design did not offer very much functionality to a user, so despite its low weight it was not ideal. He stated that the i-limb was indeed quite heavy, but that the added functionality that it provided was worth carrying the weight despite being uncomfortable. Mister Slijkhuis stated that the Delft Cylinder hand could be improved in various ways: adding a passively movable thumb, a rotational wrist and implementing various grips. These were all improvements to consider. On the other hand, he suggested me to look into decreasing the size of the batteries in the i-limb, as he thought it was an interesting aspect of the i-limb were there were still design opportunities, opposed to the mechanism of the fingers for example.
Different users prefer different devices. To narrow the crucial factors down was extremely challenging as a prosthesis is one of the most complex systems in terms of interaction as it tries to replace a hand. The ideal prosthesis for one user could be a nightmare for another, just because of their differences in lifestyles but also the height of their amputation. Someone with an amputation just below the elbow will experience much more discomfort wearing a heavy prosthesis than someone who has a lower amputation. The conclusion of the conversation with Peter Slijkhuis, was that the ratio between comfort and added functionality makes a prosthesis satisfying for a user. Minimal weight being crucial in order to make a prosthesis comfortable to wear continuously. If the ratio between those factors is optimized, the change of rejection of the device is minimized.

By gathering information from experts, literature and people experienced with protheses I defined the user needs. What user want is a **lightweight prosthetic, that adds a functionality to do various daily tasks**. The option for a natural look of the device is very important to some users, but not important at all for others. Some users even deliberately do not use the cosmetic glove of devices like the I-limb, because then they experience constant doubt if someone new they met has already seen the prosthesis. By wearing a rather noticeable device, this inner tension is dissolved immediately. Due to the wildly mixed view on cosmetic value by different users, I excluded this from my priorities but kept it in mind as a potential aspect to include.

With the gained insights of these various aspects I proceeded my design process. The myoelectric devices on the market are very functional, but uncomfortable and tiring to wear because of their heavy weight, so their ratio between comfort and functionality is not optimal. On the other hand there are body powered devices which are very light in comparison (especially the Delft Cylinder Hand), but their functionality is very limited.
The idea of implicating hydraulics in a prosthesis seemed very intriguing to me, as the weight of the Delft Cylinder Hand was revolutionary. Also, due to this concept being new, I thought there would possibly be a lot of design opportunities here. But I did not want to push this technology, so I maintained an open minded vision towards other solutions. A brainstorm session was executed in order to generate various ideas surrounding weight reduction, and the ideas that seemed promising in terms of feasibility and realization were further elaborated.

With the recent development of wireless charging and fast charging technologies which you can see being applied to mainly smartphones, I reasoned this might be applicable to myoelectric prostheses too. By doing so, the battery (hence weight) of the device could be reduced. The design challenge for me would then be as followed. The interaction with charging the prothesis multiple times a day should be integrated in such a way that is feels seamless for this approach to have more advantages than disadvantages than the current state of myoelectric devices.
I thought of various similar concepts to enable this seamless interaction with a charging method, but I after evaluating these concepts I concluded that this approach would not be viable to increase the ration between comfort and functionality. The main reason for this was that the battery was not the part that added the most mass to the device. The servos controlling the individual fingers were responsible for most of the mass, but they could not be excluded. Even if the battery could be reduced by 90% of the mass, the myoelectric prosthesis would still be very heavy, and additional downsides (charging for multiple short periods of time) would have the concept insufficient. After these concepts I concluded that reducing the weight of a multi-functional myoelectric prosthesis would not be possible. My target group, the 30% of potential users which do not actively use a prosthesis due to the weight, would most likely not be reached by implementing this idea.

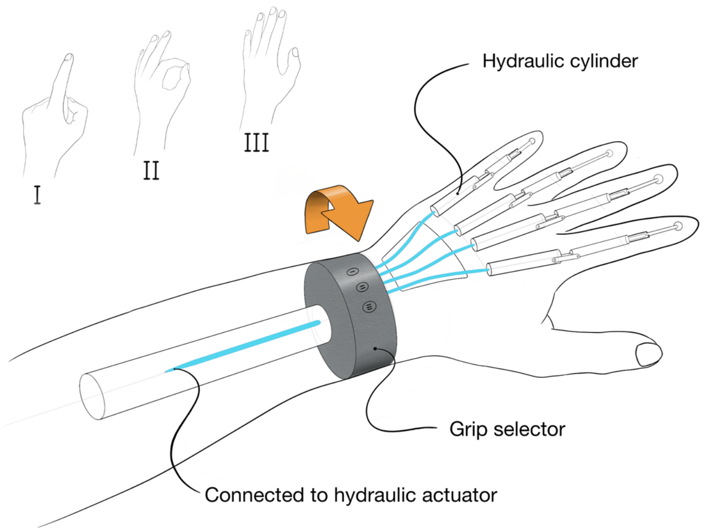
The DCH is a relatively new invention and has established a revolutionary low weight. However, its added functionality is not optimized to suit the user's needs due to the lack of various grasping methods and aspects like a rotational wrist like modern myo-electric devices include. So It does not meet the user requirements, as it does not add the functionality to do various daily tasks. In contrast to that it is easy to use and has an outstanding low weight in comparison to other devices. I was also intrigued by this concept form an entrepreneurial point of view. The concept behind the cylinder hand was relatively new, and in further developing it there were a lot of design opportunities. For this endpoint I formulated a more defined version of my design challenge.
My design challenge is to include more grasping methods in the DCH while maintaining its ease of use and low weight.



The DCH and ECH are a innovative approach compared to myoelectrical devices and body powered hands, as can be seen in the mass-functionality graph.

3. Iterations

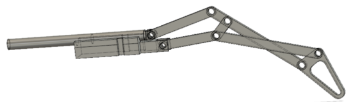
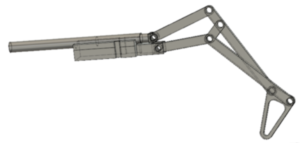
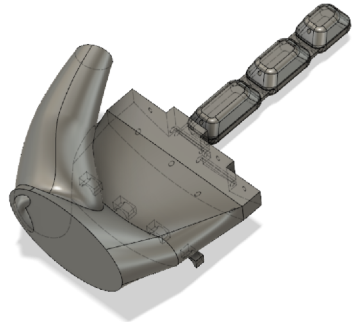
Although the DCH has a revolutionarily low weight, the prosthesis is still only limited to opening and closing the hand, making it less functional than modern myo-electric prosthetic devices. After speaking to an expert and a potential user I came to the idea to include more grasping methods which could be selected manually with the healthy hand. I decided to keep the device mechanical instead of electrical because this would maintain the lightweight properties of the DCH. I wanted to figure out which way of interaction was preferred. Was it clicking a button or rotating the wrist. Or was something preferred without the need of another hand like shaking the prosthesis?
And how many and which grips ought to be included? I decided the focus on the interaction and grips of the prothesis, instead of implementing a rotational wrist for example, like Peter Slijkhuis (from Össur) suggested. The reason being that implementing a rotational wrist would be more of a mechanical challenge rather than a design challenge.

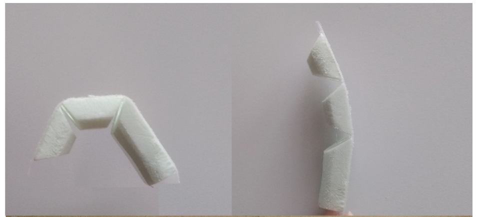
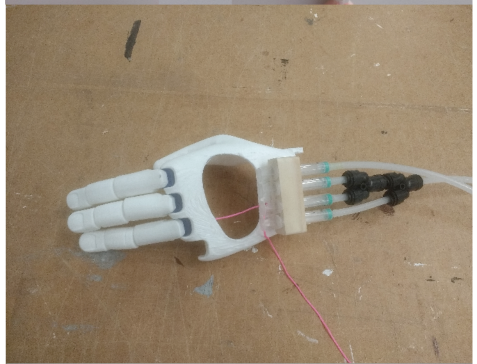
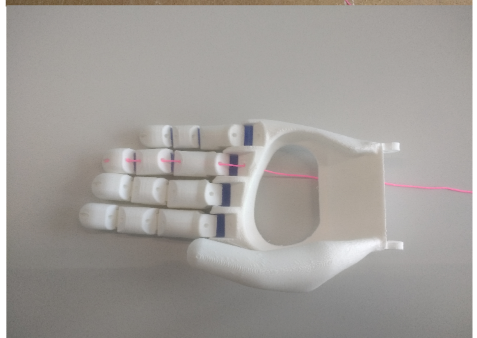
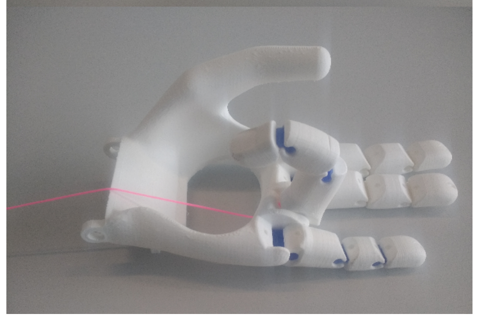


3.1.1 prototyping process

In order to get the best feedback on the concept I decided to create a physical prototype, instead of just a concept sketch. In my experience a prototype can help people imagine the fully developed product much better than a conceptual sketch can do. This often results in much more valuable input and hence improves the design process. The process of creating the prototype was exceptionally challenging, but through hard work and many iterations a working physical prototype was produced. The hydraulic cylinders were initially prototyped separately from the fingers themselves and later combined. This was done to keep the complexity to a minimum in the first phases of the process. The initial idea was to closely simulate the movement of the original cylinder hand, created at the TU Delft. As the cylinder extended, the finger closed. A very early prototype was 3D printed to test the concepts. Despite the fact that the concept worked, the idea was discarded. The reason for this was that the mechanism on which it was based was unnecessarily complex, which resulted in a fragile design prone to error. Another approach was tested in a quick way. It made use of a string which could be pulled, which resulted in the guided bending of a piece of plastic. This concept was simpler, and seemed more reliable for the purpose of this prototype. After the quick prototyping confirmed that the concept worked, I looked into ways of producing a functional prototype implementing this mechanism. Due to the complex form of a hand, I choose to use a FDM 3D printer to create the physical prototype. CAD models were created in numerous iterations, improving on each previous iteration. The program being used for creating these CAD models was Fusion 360 by Autodesk. Each individual finger consisted of three phalanges and made use of flexible connectors in between them.
these connectors were a challenge to create in a sophisticated way. The initial connectors were printed in TPU, which turned out to be too stiff; the fingers would only bend if an large amount of force was applied. The syringes that were used, which mimicked hydraulic cylinders, were not strong enough to perform this force. After that various methods were applied to improve the connectors. The shape was altered and printed in TPU again, they were casted with silicone in a mold, printed in a flexible material in a resin printer (SLA) and eventually were printed on a ultimaker 3 (FDM) printer with filaflex filament. The filaflex material was flexable enough, and regained its original shape after the actuation force was discontinued.

As stated earlier the hydraulic system was initially prototyped separately from the hand and later combined. I underestimated the exactitude which was needed for the system to perform reliably. At the first instance I wanted to implement real hydraulic syringes. However, they were not available in small sizes required for this project. I looked into ways of producing them myself, but that would result in a project of it own. I also looked into cylinders form miniature model applications. Those existed but they were incredibly expensive (more than 100€ each). Eventually I tested various medical syringes, and ended up using 3-part syringes with a volume of 2ml. These were strong enough, their friction was low compared to alternatives, and their size was still small enough for the application.
The tubes I used initially were also unable to perform the way the desired way. The material was too flexible to transfer motion from one syringe to the other. Instead of transferring the liquid inside (water) to the other syringe and moving it, the tube inflated of deflated instead. A comparable situation also happened with the first take on the tube converter, which converted one input flow to several output flows. A connector was 3D printed but showed signs of leaking, even after post treatments with various materials to improve the connection. Another method I tried was drilling holes in a material and putting in the tubes afterwards, but that failed due to similar reasons. Eventually, after a lot of searching, industrial plug in converters, industrial tubing and plug in valves were found and assembled into a working prototype of the hydraulic mechanism. The result was a big syringe that could control multiple smaller syringes. The amount of small syringes that were actuated depended on the state of the valves.
After these parts (hydraulics and hand) worked separately they were combined into a functional cylinder hand. The prototyping phase took quite long so this is where I stopped. Initially I also wanted to include some way of operating the device with the shoulders, like the final product would do. However, at this stage the questions I had about the interaction with the device could be answered by discussing the prototype in the stage I was at this moment. As stated earlier I wanted to have a physical prototype to discuss with both experts and users, instead of just the concept in my head. In my opinion a prototype is often a useful tool to show people the potential of an idea, as it is one step closer to realization than a concept drawing. It showed people the potential of the technology, but is was still quite bulky and did not resemble the product I had in mind, so besides the physical prototype I also included drawings of the concept with a more refined finish.

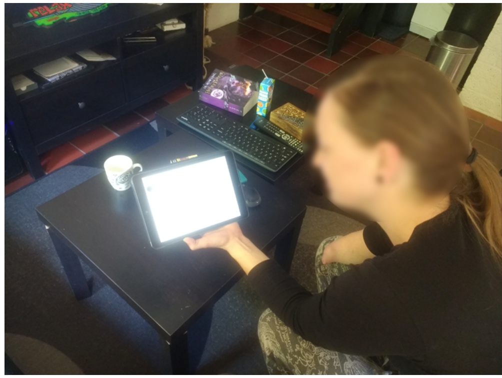
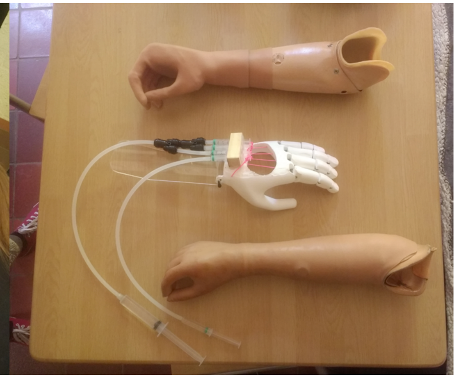





After realizing the Prototype I proceeded with evaluating the initial design with another expert to gain a broader perspective. This expert, Marielle Lukassen, was involved with the training people with arm injuries including people with prostheses at Adelante. Although she were intrigued by the concept of the cylinder hand, the conclusion of this this meeting was that the interaction shaped this was would take to long, and the user would already have done the task with their healthy hand instead. The switching between grips would not be feasible if the healthy hand needs to be involved.

This was in contrast to the what my earlier findings were, based on the opinion of a anatomically incomplete person. However, that person had a congenital malformation, and had very little experience with prostheses because the person was used to doing everything without it since childhood. I was mistaken to interpreted that persons vision on and experience with the interaction with prostheses as universally true, as this person had never used a prosthesis actively. Therefore that persons expectations of the interaction with a prosthesis were not realistic unfortunately.

Another person I spoke to, which did actively use a prosthesis, confirmed this new finding that a prosthesis should be controllable without using the healthy hand. We talked about all experiences with protheses from as soon as childhood. As a child the body powered hook was being applied and actively used. But when reaching a certain age, the transition towards myo-electric prostheses had been made. Initially it was a fairly simple prosthesis, which could only open and close, but later a i-limb was provided by the person's insurance. Although it had many different functions and was far more advanced, the person was not very fond of this device. The learning process of the input patterns was complex and took a long time. And it often happened that the device misunderstood the persons input, and a wrong grasping method was being activated. In cases like these, instead of trying it again with the prosthesis, the task at hand would often already be completed with the other hand. When having this conversation it all sounded very logical, but it was a point of view which I would not have been able to take without actively speaking to users.

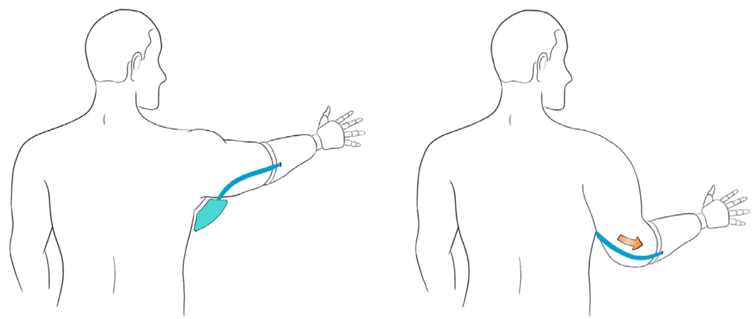
This was a clear indication that the interaction with the device had to be actuated with the (part of) the arm that the prosthesis was going to be equipped to. It was also very interesting for me to observe that the traditional myoelectric prosthesis was preferred over the i-limb even though its functions were a lot more limited. The reason being that the actuation of the i-limb was complex and even after training the device still misinterpreted the input signals wrongly on a regular basis. After diving into literature concerning the ease of use of a prosthesis, this user's statements were confirmed. An important factor in the acceptance of a prosthesis is the ease with which the wearer can operate the device (Kyberd et. al., 1995). Another paper also described ease of use as a basic requirement for aprosthesis (Plettenburg et. al., 1998). In hindsight, adding the extra step of selecting the desired grip with the healthy hand is in fact an interfering factor in terms of ease of use, and should be logically eliminated. Based on these insights I developed a new iteration which implicated the knowledge drawn for the users, expert opinions and literature.

3.2 ease of use & functionality

With the first iteration and the insights it had provided the design process was continued. The design challenge was modified to: the design challenge is to include more grasping methods that add functionality to do various daily tasks, and which is easy to use and can be managed without using the healthy limbs. (while maintaining the DCH's low weight).
Various ways of the interaction were researched, where the state of the device could be controlled without making use of the healthy hand. Again the initial ideas were to keep it mechanical instead of electric, due to batteries natural added weight. This is a property that cannot be altered. After a brainstorm session various ideas were generated, elaborated and eventually the best option was chosen.

3.2.1 A way of switching mechanically could be ideal theoretically, due to the fact that a solution like this would likely be less heavy than applying electrical sensors and other electrical parts. But when thinking of new mechanism and research existing ones it turned out not to be the optimal solution for the problem. A concept was to control a hydraulic valve by squeezing a balloon with the armpit. However this interaction is quite slow because requires an extra physical movement which likely to cause overuse or compensatory motion which should be avoided (Highsmith et. al., 2008). Also, due to the extra part which needs to be attached to the body and worn all day, this solution will likely be very uncomfortable to use. Sweat will also very likely be a problem with a design like this. Besides those arguments, controlling a hydraulic valve like this will likely only be able to vary between two states, opposed to other solutions.

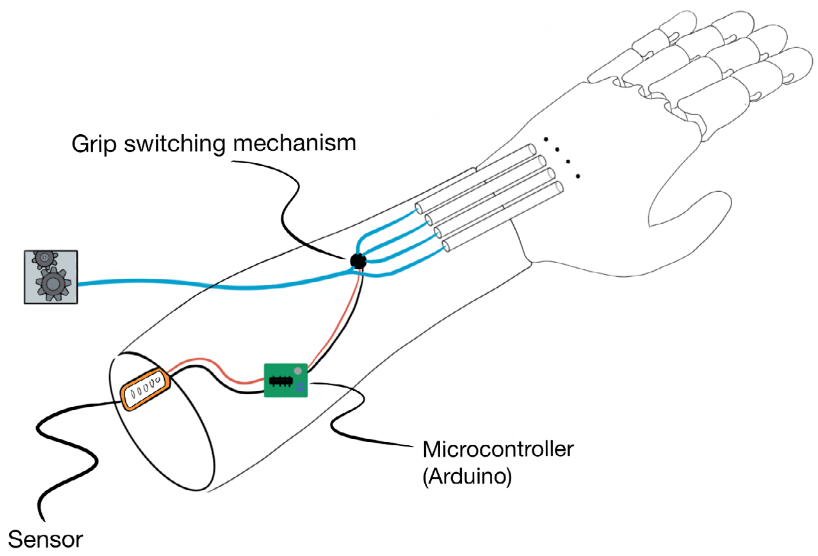


3.2.2 A technology that is very promising for optimizing the ease of use is artificial intelligence in the form of pattern recognition. Machine learning can be applied to optimize the precision of this technology, resulting in an interaction between an amputee and prosthesis which feels seamless. However there are two downsides that go along with implementing this technology for a prosthesis. First of all pattern recognition does not work for people with congenital anomalies because those people have never learned to move various muscles in a pattern to manipulate object with their hand. Due to this fact is would then only be applicable to amputees, but even for them this technology is not the best solution despite its ease of use. EMG sensor bracelets are capable of measuring muscle activity across the whole arm but these sensors are large and very noticeable, and even more importantly they are very heavy which is in conflict with the design challenge.

3.2.3 traditional EMG sensors are the most suitable for this application. Traditional meaning that they only aim to measure the activity of one muscle. These sensors can be used by both amputees and people with congenital malformations. They are very light in comparison to myoelectrical sensors which aim to measure all muscle activity and are used for pattern recognition.
Ideally only one sensor will be used. This would minimize the weight as another sensor is excluded, but the minimal battery capacity is also lower, hence its weight.
The question is if the interaction of the device with only one input is still manageable and is experienced easy by the user, as the ease with which the wearer can operate the device is an important factor for the acceptance of a prosthesis (Kyberd et. al., 1995). Based on this research a new concept was developed which integrated a myoelectric (EMG) sensor, a microcontroller and an electrically controllable valve. This valve would either enable or disable the movement of certain fingers.
The actuation of the fingers themselves is still being done by operating the master cylinder on the users back, in order to maintain the wanted low weight, quick reaction and feedback opposed to prostheses like the i-limb. The added system which consist of the micro controller, valve, battery and EMG sensor would increase the weight of the prosthesis, but the estimated weight of the device would still be far lower than a myoelectric device.

The reason being that standard myoelectric devices make use of one big battery which must actuate different servo's all day, and the servos and battery are responsible for most of the weight in these devices. Also the position of the weight in a myoelectric prosthesis is far from the remaining part of the arm because that is where the servo's are placed. The added weight in comparison with the original Delft Cylinder Hand could be integrated close to the remaining part of the arm, minimizing the perceived weight of the device.

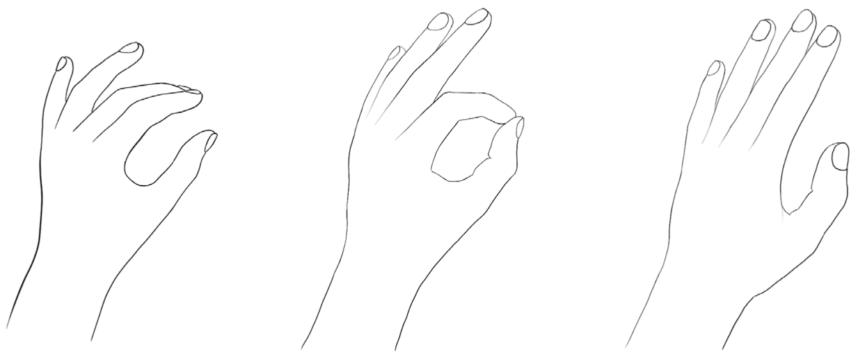
The challenge now is to optimize the interaction with the EMG sensor, or possibly add another EMG sensor to keep the interaction streamlined. In the next section the control of the sensor will be elaborated. Also the various grips that are essential will be discussed.



3.3 Focus on Interaction

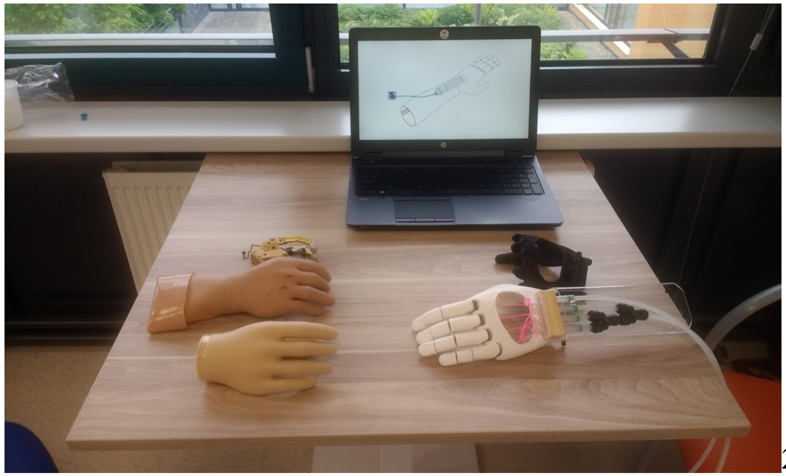
The new concept was discussed with Frenk Peters, a prosthetist active at the Sint Maartenskliniek located in Nijmegen. He is a field expert and has decennia of experience in equipping patient with custom prostheses, integrating their personal needs. I introduced him to my project and he was quite optimistic about the approach. What I wanted to discuss with him was the following: how can the user experience be optimized by establishing a balance between added functionality and easy of use. The more grips are included, the more functional the device. But an unwanted side effect of these added functions is that the interaction becomes very complex very quickly. Vice versa when the interaction is at its most simple, the functionality would be minimized.

From literature I found that three grips are most essential in every day tasks. Precision and lateral grips are the mostly used grips in daily activities (Matrone et. al., 2011). The power grip consists of all fingers, the precision grip makes use of the index finger and the thumb, and finally the lateral grip makes use of the index finger, middle finger and thumb.



The lateral grip, precision grip and power grip

I wanted to involve Frenk Peters expert opinion on which grips to include in the device, and which were obsolete. In his opinion reliability was essential, and the three grips that were just mentioned would be satisfying for the majority of people for the majority of tasks. This matched the conclusion of my previous interview with an experienced prosthesis user. Their experience with the i-limb was that the complexity of the device was over the top and in practice only few grips were used. Added to that the device often misinterpreted the input signals, which resulted in a wrong grip being actuated. In the mean time the task would often already be done with the other hand instead of sending a new input signal.



3.3.1 prototyping of the sensor

In order to optimize the interaction with the prosthesis the input that the user gives to the sensor should be simple so that it can eventually become second nature, and the prosthesis can be used without any cognitive attention. In the next section the prototyping process of the sensor will be explained, followed by the user test and validation in the next section.

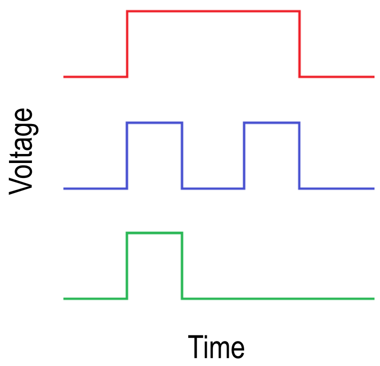
Original EMG sensor which are used in state of the art prosthesis are not commercially available for consumers. There are EMG sensors on the market produced by Myoware, however they are expensive (80€+) and bulky. Besides that the prototype of the cylinder hand had already cost more than I estimated the whole project would cost. Due to that I researched other options which could possibly provide a solution. Force sensitive resistors seemed promising at the first glance, so I went on the buy one and placed it in an elastic bracelet. I wrote a very simple arduino code to test the concept and it worked. The sensor was placed tightly to the skin of my under arm, and by tensioning my muscles I was able to control a binary system (turning on and of an led in this case). However, the sensor was very intensive to control in terms of muscle tension and its accuracy was not optimal for this application.

It was very important that the sensor itself would work reliably and seamlessly, otherwise testing the interaction would not be viable. If the sensor would not work reliably, the outcome of the user test would not be credible, because the main feedback would revolve around its reliability and not the interaction itself. While prototyping this sensor I was also thinking about the user test set up, which I discussed with Frenk Peters from the Sint Maartens clinic in Nijmegen. Being interested in the project he provided me with an original EMG sensor from a discarded Ottobock prosthesis. For the second iteration of the sensor I used a breadboard and jumper cables to assemble the Arduino Uno, the sensor and the led's.

As stated earlier, the interaction with the sensor ought to be seamless. For that reason I made two decisions. First of all I defined the input signals that the sensor should be able to distinguish. I choose to implement three varying inputs: a single short muscle contraction, a double short muscle contraction and a long muscle contraction. I choose these because they easy to remember for a user and easily distinguishable data wise.The device should be able to react fast so the long muscle contraction would be around one second. The same is true for the timespan in which the two short muscle contractions would be actuated after each other. Secondly I chose to test the interaction with the sensor separately from the prototype of the cylinder hand. The reason for this being the lack of necessity to combine them, in order to determine the optimal interaction with the sensor, which was the focus of the project at this point.

After the initial testing with the sensor I proceeded to make the sensor more wearable so that it could be tested more thoroughly and in a more mobile manner. This property was key in my opinion to validate the outcomes of the user tests because it eliminates any limitations in freedom of movement. In order to establish this small size a special arduino was chosen, namely the Digispark ATtiny 85. Although it has a limited amount of pins and computational power, it was perfect for this project due to its incredibly small size (18x23mm). After numerous versions of code, the sensor was finally reactive and worked reliably. The main challenge in this process was the data interpretation and the sensitivity of the sensor. The time spend to provide a “double click” varies among persons, yet the output should be the same. Also, the measured voltage in a muscle varies between individuals. In order to overcome those differences an auto calibration was implemented in the Arduino code, after various tries of determining an universal threshold value. The arduino code can be found in the appendix.

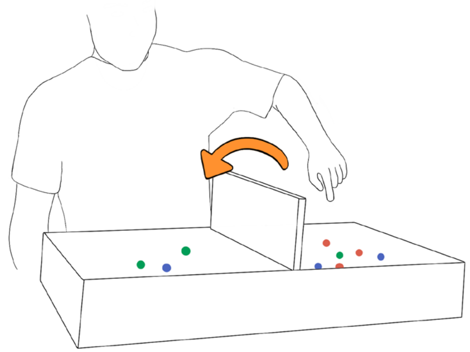
A digital addressable RGB-led was used to visualize the sensors interpretation of the sensor input. A single short muscle contraction would make the led light up green, a double short muscle contraction would make the led light up blue and a long muscle contraction would make the led light up red.

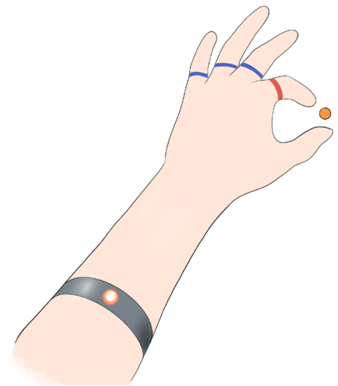


After testing the sensor thoroughly a casing was design in Fusion 360 and 3D printed on a FDM printer. An elastic bracelet was attached to the casing to make the sensor truly wearable and maintain comfort and freedom in terms of movement. The result of this prototyping process was a truly wearable sensor, which worked seamlessly and was able to clearly distinguish between the thee inputs. After turning on the sensor, it would ask the user to relax their muscle, and after that to contract their muscle in order to calibrate the sensor and determine the threshold value which needed to be surpassed in order for the sensor to react. By doing this, unintentional and small muscle contractions would not be registered/reacted upon.
The only “flaw” the sensor still had was that its placement was still crucial in order for the sensor to work properly. This limitation however is caused by the technology of the sensor and not the coding. When a real prosthesis is created and custom fitted to a user, this is always done in such a matter that the sensor placement is considered thoroughly and errors caused by this are eliminated.

3.2.2 User Test & validation

For user test of the interaction with the sensor a mixed method approach was applied. I wanted to make use of a mixed methods approach because both qualitative and quantitative data are very valuable in gaining insights in the workings of the design and in the user perspective. Due to the lack of prothesis users that I could do a user test with, the interaction was tested with anatomically intact people. This was not ideal of course, but it was the best option at this stage of the project to gain insights in the interaction with the sensor. During the test they were only allowed to perform a certain grasping method (precision grip for example) after they successfully interacted with the sensor. See the image for clarification. I constructed a set up in order to measure a task completion time in order to generate objective data, and after that the users would be asked several questions. These questions would be formed in such a way that the participant reads a statement, and can answer whether they agree or disagree with a statement with a scale from one to seven. This is done in order to try to eliminate the suggestive character of asking direct question. I wanted to further eliminate flaws in my approach regarding qualitative research, and applied theories from “Real world research: a resource for social scientists and practitioner-researchers” for doing so (Robson, 2002). One of the theories I applied was “peer debriefing” which encourages the researcher to let the research/test set up be reviewed by another person which is familiar with the context. So in order to discuss my user test set up I contacted Siete Sirag, teacher at Fontys and an expert in the field of orthopedic technology. He suggested that in order to improve the user test, the task should be a realistic setting instead of a hypothetical one. So the initial test which involved moving colored object from one reservoir to another was discarded, and another test set up was developed. It was based around a task which involved all thee grips and was a very “normal” task; preparing a serving tray. One can and two cups should be placed on the serving tray making use of the power grip, followed by two spoon that are manipulated by the lateral grip, and finally two cubes of sugar with the precision grip. By chancing the hypothetical scenario to a more realistic set of actions, my test persons would be encouraged to imagine the real life applications in a more concrete manner.





I tested two versions of the interaction. One in which each grip had a specific sensor input (single, double, long) and needed a new input for every grasping motion to be done. In other words the sensor did not "remember" the last grips that was used and needed a new input when a new object was to be grasped. The reason for this was that if the device did "remember" the selected grip a feedback mechanism would have to be implemented for a streamlined interaction, and this would increase the complexity of the device unnecessarily.
The other version were the lateral grip was set as default and did not need an input from the sensor to be performed, opposed to the other grips. And the other grips were selected by giving a sensor input specific to that grip. I chose the use a long sensor input (red) for the power grip, and a single short input for the precision grip (green). The reasoning behind this was metaphorical; a short input resembling a small object hence the precision grip, and the long input resembling a larger object hence a power grip. These links between grips and sensor input were not final, but I had to decide upon something in order to test the interaction.
The time task completion time of the different versions were measured and afterwards interviews were conducted in order to gain a deeper understanding of the user experience. Which interaction was preferred and for what reasons?

User feedback

from the conducted research I concluded that a the least favorable sensor input was the long muscle tension (red). Participants stated that the movement felt unnatural, could cause muscle aches (cramps) and that the reaction time was longer than the other inputs. Logically, the single short input (green) was preferred over the double short input (blue) as it was easier to perform. Furthermore I concluded that the version with default grip was preferable compared to a version without one from both statements and the measured task completion time. The default grip would remain the lateral grip because it is the best compromise between being able to pick up fairly small and fairly large objects and would be more broadly applicable than either the power- or precision grip. However, this result remains debatable as it has not been tested with real prosthesis users.

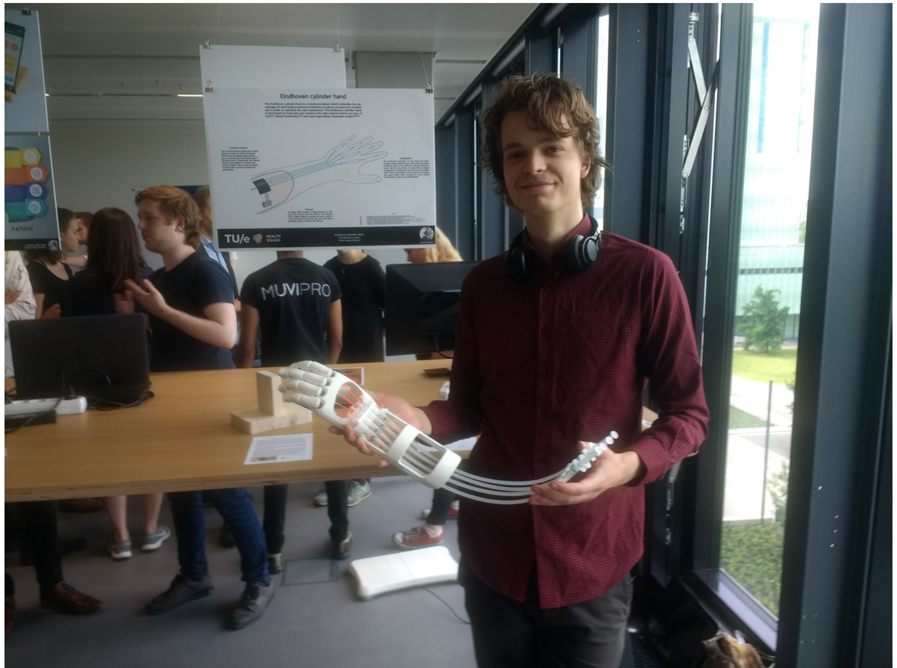
Expert feedback

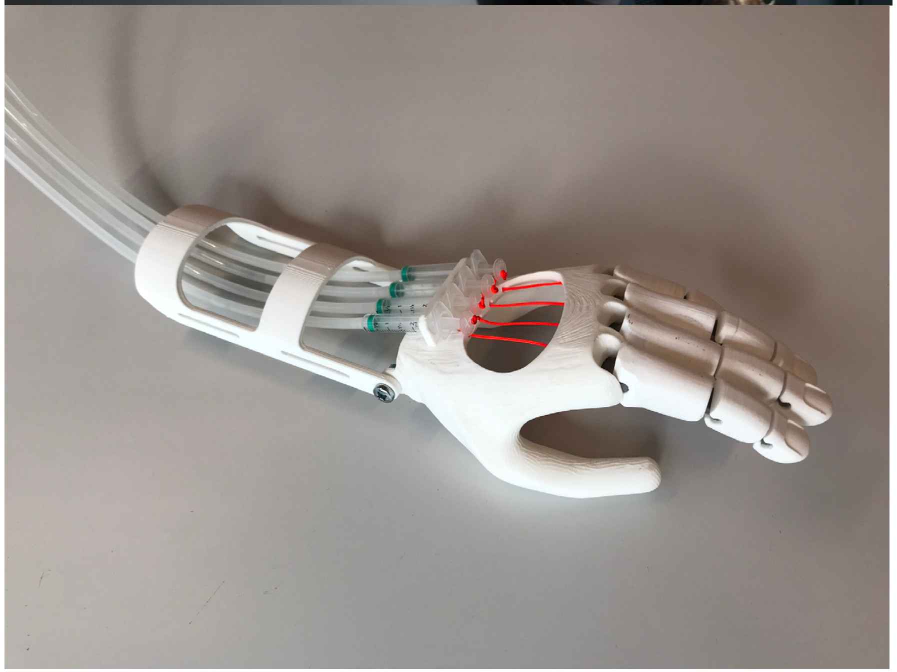
When reviewing the this outcome with Frenk Peters, he provided me with valuable information. A myoelectric prosthesis could hold on to an object once it has been grasped, and the cylinder hand could only do that if the device was being kept actuated by applying force with the shoulders. Traditional body powered hooks solved this problem by optionally being a "voluntary open" device if this was preferred by the user. A device like this would always remain closed, but could be opened if actuated by the shoulders, opposed to the cylinder hand in this state. However, a similar result could be realized by integrating a "master valve" which could freeze the cylinder hand in the current position. By doing so a object that was grasped could be kept in place, while the tension of the shoulders which closes the hand was dismissed. This master valve could then be controlled by the long muscle tension input to the sensor (red). This would also metaphorically make sense to hold an object. I will give an example to clarify the interaction. Suppose you would want to grab an object, and would have to hold it for a minute before giving it to someone else. Then you could now actuate the cylinder hand with your shoulders and the object would be grasped with a lateral grip (because it is the default so no sensor input is needed). If a sustained muscle tension is measured by the sensor (red) the hand will be locked into position and the object will stay put, even after the actuation force is discontinued. In order to release the object again, after walking a certain distance for example, a single short input (green) will be provided to the device and the object can be released. Implementing this option would make the interaction with the device not too complex in comparison when it is excluded, but it does improve the convenience of the for holding objects, resulting in an interaction similar to a myoelectric prosthesis.

4. Demo Day and Conclusion

For the Demo Day I prepared separate prototypes of the cylinder hand, the sensor and the hydraulic mechanism. These were presented separately in order to demonstrate all functions in a clear manner. A conceptual sketch was depicted on the poster where all separate parts of the design were combined and visualized as one functional device. A summary of the design process was included as well as the main features of the prosthesis.
The final prototype of the cylinder hand and sensor were presented with a caption to further clarify how it worked and the reasoning behind the design choices. These captions can be found in the Appendix.

Valuable feedback was gained during the Demo day by various people, including my coach Daniel Tetteroo and Richard Geers from Adelante, the design could possibly be improved by gathering more input from end users. Due to the scarcity of prosthesis users that I could involve in my design process a significant amount of design choices were made based on literature and expert opinions. Although this is not wrong by any means, involving more users would of course be preferable. I also tried to elaborate on the estimated costs of my final design, but due to the fact that the prices are unknown of many parts this estimation would be indefinite. The cylinder hand itself would cost around 8000€ according to Gerwin Smit, excluding the custom fitting. The costs of the added parts, consisting of the sensor and control center, are also up for discussion. This is mainly because the control center is conceptual right now and has to be developed by mechanical and electrical engineers. Without that the estimation of both the price and energy consumption are debatable. However the energy consumption will be logically be less than that of a myoelectric prosthesis due to the fact that the actuation of the fingers is still body powered and the valves do not consume energy constantly, but only when their state is changed.



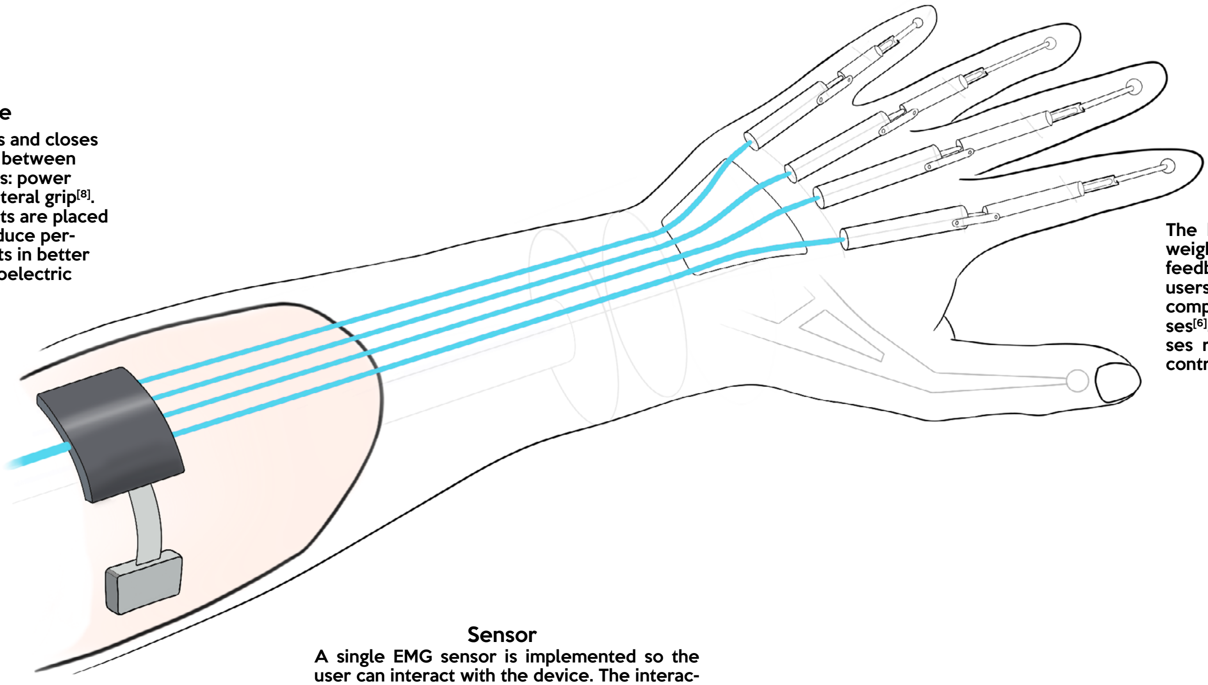


Eindhoven cylinder hand

The Eindhoven cylinder hand is a hybrid prosthesis which embodies the advantages of both body-powered prostheses as well as myoelectric prostheses in order to optimize the user experience. The Eindhoven cylinder hand is developed to imply the user needs in the right balance which are ease of use[1][2], added funtionality[3][4] and most importantly minimized weight[5][6][7].

Control centre

The control centre opens and closes valves in order to switch between three most essential grips: power grip, precision grip and lateral grip[8]. All electronic components are placed close to the elbow to reduce perceived weight. This results in better comfort than current myoelectric prostheses.



Hydraulics

The hydraulic cylinders in the hand are lightweight and provide the user with proprioceptive feedback. Due to the efficient energy tranistion, users will be less likely to experience fatigue compared to traditional body powered prostheses[6]. Most importantly body powered prostheses react faster than myoelectric ones, which contributes to the user experience[4].

Sensor

A single EMG sensor is implemented so the user can interact with the device. The interaction is kept simple to satisfy the user needs [1] [2]. By tensing the muscles the user can switch between grips or freeze the device.

Sources:

[1] P.J. Kyberd et. al, a two degree of freedom hand prosthesis with hierarchical grip control 1995
[2] D. H. Plettenburg et. al, Basic requirements for upper extremity prostheses:The Wilmer approach, 1998
[3] TW Wright et al. Prosthetic usage in major upper extremity amputations, 1995
[4] S.L. Cary et al, Differences in myoelectric and body-powered upper-limb prostheses: systematic literature review, 2015
[5] L.E. Pezzin et al, Use and satisfaction with prosthetic limb devices and related services, 2004
[6] G. Smit et al, The Lightweight Delft Cylinder Hand: First Multi-Articulating Hand That Meets the Basic User Requirements, 2015
[7] E. Biddiss et al, Consumer design priorities for upper limb prosthetics, 2007
[8] G. Matrone et. Al, Two-channel real-time EMG control of a dexterous hand prosthesis, 2011

Jesse Janssen

5. Recommendations & future

During the course of my final bachelors project I came into contact with Ilse Leijen, a mechanical engineering student who is interested in the further development of the Eindhoven Cylinder Hand, and will focus on the engineering of the device. I will prepare as much helpful information for her as possible in the form of scientific literature to read, contact information of experts and users that were involved in my design process etc. I hope to stay involved in the further development of the cylinder hand, and I am excited for the future regarding this innovation.

Besides this wonderful opportunity to pass on my project I was also asked to demonstrate my prototype at the Fysio Xperience on the 14th of June in Strijp-S Einhoven. At this exhibition which is I hope to gather more feedback form experts on my design process, and possibly find other enthusiast to further develop the Eindhoven Cylinder Hand into a fully functional prosthesis. If this happens the prototype can be tested thoroughly by users for extended periods of time, which was not possible during my design process unfortunately. With the feedback gained a final product could be made, which would be a dream come true for me.

6. Acknowledgements

I would like to express my appreciation for all the people who helped making this project possible. I want to thank the following people in particular:

Daniel Tetteroo, Roos Van Berkel, Gerwin Smit, Richard Geers, Marielle Lukassen, Frenk Peters and Peter Slijkhuis.

Thank you for your time, input and guidance. It is sincerely appreciated.

7. References

Smit, G., Plettenburg, D., Van Der Helm, F.C.T.(2015) The Lightweight Delft Cylinder Hand: First Multi-Articulating Hand That Meets the Basic User Requirements. Retrieved from: https://www.researchgate.net/publication/264795880_The_Lightweight_Delft_Cylinder_Hand_the_First_Multi-Articulating_Hand_That_Meets_the_Basic_User_Requirements

Carey, S.L., Lura, D.J., Highsmith M.J. (2015). Differences in myoelectric and body-powered upper-limb prostheses: systematic literature review. Retrieved from: https://www.ncbi.nlm.nih.gov/pubmed/26230500 (including the images of the Delft Cylinder Hand).

Pezzin, L.E., Dillingham, T.R., MacKenzie, E.J., Ephraim, P., Rossbach P. Use and satisfaction with prosthetic limb devices and related services (2004). Retrieved from https://www.archives-pmr.org/article/S0003-9993(03)00896-7/abstract

Biddiss, e., Beaton, D., Chau, T., (2009) “Consumer design priorities for upper limb prosthetics, retrieved from https://www.tandfonline.com/doi/full/10.1080/17483100701714733?scroll=top&needAccess=true

Plettenburg, D.H., “Basic requirements for upper extremity prostheses:The Wilmer approach (1998). Retrieved from https://ieeexplore.ieee.org/document/744691

Smit. G., Bongers R.M., Sluis, C.K., Plettenburg, D.H. Efficiency of voluntary opening hand and hook prosthetic devices:24 years of development? (2012). retrieved from https://www.rehab.research.va.gov/jour/2012/494/pdf/page523.pdf

Wright, T.W., Hagen, A.D., Wood, M.B. Prosthetic usage in major upper extremity amputations(1995). Retrieved from: https://www.sciencedirect.com/science/article/pii/S0363502305802783

Highsmith, J.M., Carey, S.L., Maitland M.E., Dubey, R.V. Compensatory movements of transradial prosthesis users during common tasks (2008). retrieved from https://www.sciencedirect.com/science/article/pii/S0268003308002040

Biddiss, E.A., Chau T.T., Upper limb prosthesis use and abandonment: A survey of the last 25 years (2007). Retrieved from: https://journals.sagepub.com/doi/full/10.1080/03093640600994581#_i30

Kyberd, P.J., Holland, O.E., Chappell, P.H., Smith, S.,Tregidgo, R.,Bagwell, P.J.,Snaith, M.
a two degree of freedom hand prosthesis with hierarchical grip control (1995). Retrieved from: https://ieeexplore.ieee.org/abstract/document/372895

Matrone, G., Cipriani, C., Carrozza, M. C., Magenes, G. Two-channel real-time EMG control of a dexterous hand prosthesis (2011). Retrieved from: https://ieeexplore.ieee.org/abstract/document/5910608

Robson, C. (2002). Real world research: a resource for social scientists and practitioner-researchers. Retrieved from http://www.dem.fmed.uc.pt/Bibliografia/Livros_Educacao_Medica/Livro34.pdf

Image references:

Body powered hook
Ottobock, date unknown. Retrieved from https://media.ottobock.com/prosthetics/arms/_general/images/below_elbow_body_powered_prothesis_graphic_16_9_teaser_onecolumn.jpg

Body powered posthesis
Ottobock, date unknown. Retrieved from https://www.ottobockus.com/media/local-media/prosthetics/upper-limb/body_powered_solution_1_1_teaser_fallback.jpg

I-limb
Össur, date unknown. Retrieved from https://assets.ossur.com/library/39653/proc/6/i-limbquantum.png

Gerwin Smit

Author unknown, date unknown, retrieved from https://d1rkab7tlqy5f1.cloudfront.net/_processed_/9/4/csm_gerwin2_00c9d5f068.jpg

All other visuals are created by me.

8. Appendix

Appendix A: User Questionaire

ENQUÊTE PROTHESE

Naam:	
Leeftijd:	
Geslacht:	

Ga je er mee akkoord dat dit gebruikt wordt in mijn verslag en mag ik jouw naam erbij zetten?
ja/nee

Vraag	Mate van belangrijkheid				
	Helemaal oneens	Deels oneens	neutraal	Enigszins	Totaal mee eens
Comfort is belangrijker dan functionaliteit	1	2	3	4	5
Eenvoudig gebruikt is belangrijker dan functionaliteit	1	2	3	4	5
Eenvoudig gebruik is belangrijker dan uiterlijk	1	2	3	4	5
Eenvoudig gebruik is belangrijker dan comfort	1	2	3	4	5
Robuustheid is belangrijker dan comfort	1	2	3	4	5
Robuustheid is belangrijker dan functionaliteit	1	2	3	4	5
Robuustheid is belangrijker dan uiterlijk	1	2	3	4	5
Uiterlijk is belangrijker dan comfort	1	2	3	4	5
Het is niet erg dat ik niet alles kan met mijn prothese	1	2	3	4	5
Functionaliteit is belangrijker dan uiterlijk (niet perse realistisch)	1	2	3	4	5
Een BP prothese kost teveel kracht op een dag	1	2	3	4	5
Handmatig/fysiek wisselen van greep is oke	1	2	3	4	5
Een prothese mag geen onderhoud kosten	1	2	3	4	5
Precisie van grepen is essentieel	1	2	3	4	5
Kunnen typen met een prothese is belangrijk	1	2	3	4	5
Verschillende grepen zijn essentieel is een prothese	1	2	3	4	5
Het is niet erg dat ik niet alles kan met mijn prothese	1	2	3	4	5
Protheses zijn doorgaans te zwaar	1	2	3	4	5
Het is niet erg dat mijn prothese minimaal onderhoud nodig heeft	1	2	3	4	5
Comfort is het belangrijkste aan een prothese	1	2	3	4	5
Gebruikersgemak is het belangrijkste aspect aan een prothese	1	2	3	4	5
Functionaliteit is het belangrijkste aspect aan een prothese	1	2	3	4	5
uiterlijk is het belangrijkste aspect aan een prothese het is echt een combi van alle aspecten (robuustheid is het minst belangrijk).	1	2	3	4	5

Hoe komt het dat je een hand mist?

Heb je vroeger protheses gedragen?

wat is de rede/zijn de redenen waarom je geen prothese gebruikt?

Wat was goed aan de prothese de je gebruikt hebt?

ervaarde je de prothese als te zwaar?.

heb je ervaring/een mening over myo-elektrische protheses?

Heb je ervaring/een mening over lichaamsbekrachtigde protheses?

wat kan je nu niet en zou je graag (makkelijker) willen kunnen met een prothese?

welke grepen zijn volgens jou essentieel?

Appendix B: User Questionaire Sensor

In this user test a mixed methods approach is being applied. Quantitative data will be created by measuring task completion time, and qualitative data will be the result this questionnaires. The following is a description of the step by step execution of the user test.

1. Prepare by placing the items on the table that will be involved. Place the sensor on the table.

2. Introduce the subject to the project, and explain the goal of the user test to them.

3. Ask the subject if he/she is okay with using the to be generated data for the study, and ask them to sign the consent from.

4. Show how the sensor is calibrated, and how it reacts to the three input types (short, double and long).

5. Put on the and calibrate the sensor together. Help them in gaining control over the sensor output.

6. Start the tasks and measure their completion time with a stopwatch.

7. Ask the following questions after each task-profile combination. (1= totally disagree, 7=totally agree)

1. The sensor reacted too fast	1/7
2. The sensor reacted reliably in general	1/7
2. The single input was comfortable to use	1/7
3. The double input was comfortable to use	1/7
4. The long input was comfortable to use	1/7
2. The single input was easy to control	1/7
3. The double input was easy to control	1/7
4. The long input was easy to control	1/7
5. It was preferable that there was no default grip	1/7
6. It was preferable that there was a default grip	1/7
7. The overall experience of interaction was enjoyable	1/7
8. The overall experience was not complicated	1/7
9. The overall experience of interaction hard to control	1/7
10. The overall experience of interaction intuitive	1/7

Appendix C: concent form

Consent Form

Participation

Hereby I consent to take participate in this user study in a voluntary basis and I understand that I am not obligated to answer a question without having to give a reason. I understand that I can withdraw from the user test at any given moment without consequences.	[agree / disagree]

Generated information

I consent that the generated information can be used for research purposes.	[agree / disagree]
I consent to have my personal information collected as long my identity is not shared beyond the Technical University of Eindhoven.	[agree / disagree]

Signature:

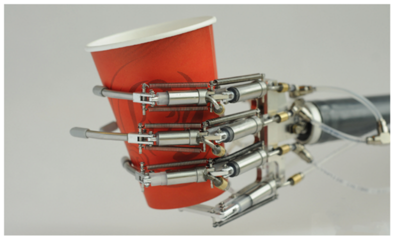
____

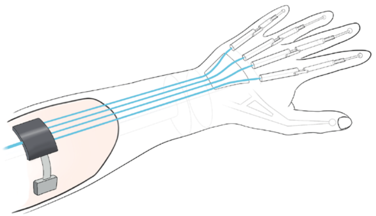
Concept of the Eindhoven cylinder hand

Nearly one-third of prosthetic users is dissatisfied with the comfort of their prosthetic device. Due to the high weights of prosthetic hands, up to 30% of amputees do not actively use a prothesis[5] [6]. Reduced prosthesis weight emerged as the highest priority design concern of consumers[7]. Primary indicators of prosthesis rejection include lack of perceived functional gains and prosthesis weight[3]. Users often cite that the functional advantage or cosmesis does not outweigh the discomfort or inconvenience of the device[4]. Besides reduced weight, ease of use is a crucial factor to reduce the chance of prosthesis rejection[1][2]. The Eindhoven cylinder hand was developed to implement these criteria in a balanced way.

Body-powered protheses are lightweight and easy to use but optimizing these factors is in the expense of the limited functionality. Myoelectric devices are able to perform various grips but they are hard to control and very uncomfortable to wear due to due to their high weight.

The Delft Cylinder Hand was developed to answer the demand for lightweight prostheses. Weighing only 150 grams it is the most lightweight functional prosthetic hand in the world. However, the functionality is limited to opening and closing the device. A design opportunity presented itself. The Eindhoven Cylinder Hand is based on the Delft cyinder hand, but aims to encompass the advantages of both myoelectric- and body powered prostheses, by adding more grips to the original Delft Cylinder Hand.
The grips were limited to only the most essential, in order to optimize the reliability and ease of use of the device[1][2]. Only the mostly used grips in daily activities were implemented. Those are the precision grip, lateral grip and the power grip[8].

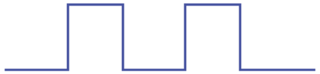




The Sensor

The grips of the Eindhoven Cylinder Hand can be controlled by tensioning muscles in the remaining part of the Arm. Ease of use is very important for prosthetic users[1][2]. That is why the interaction with the Eindhoven Cylinder Hand is developed to work reliably and is easy to control. Users I spoke to were often dissatisfied with the control of their myoelectric device because the interaction was too complex and the device often misinterpreted their input. Ironically, only a few grips would be used on a daily basis. The sensor of the Eindhoven Cylinder Hand can reliably distinguish three types of input. A single short tension, a double short tension and a long tension of the muscle.

The long input is used to freeze the prosthesis, so an object can be held

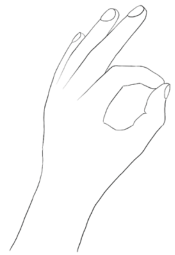


By giving a double short input the prosthesis switches to a power grip

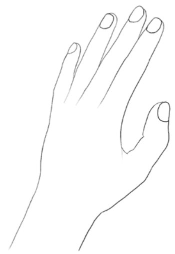
By giving a single short input the prosthesis switches to a precision grip.

The default grip of the prosthesis is the lateral grip.

lateral grip



precision grip



power grip

Appendix E: Arduino Code

```
include <Adafruit_NeoPixel.h>
#define PIN 1
Adafruit_NeoPixel strip = Adafruit_NeoPixel(1, PIN, NEO_GRB + NEO_KHZ800); // include the library to control
digital RGB leds.


int pad = A2; // declairing pins and variables.
int ledOn = 0;
int drempel;
int calLow;
int calHi;
int reading = 0;
int reading1 = 0;
int reading2 = 0;
int reading3 = 0;
int reading4 = 0;
int reading5 = 0;
int reading6 = 0;
int reading7 = 0;
int reading8 = 0;
float D1 = 0;
float D2 = 0;
float Dtot = 0;

void setup() {
  strip.begin();
  strip.show();
  pinMode(pad, INPUT);

  strip.setPixelColor(0, 35, 25, 0); // callibrate the value of a relaxed muscle, while a yellow led is on.
  strip.show();
  delay(500);
  calLow = (analogRead(pad));
  delay(500);
  strip.setPixelColor(0, 0, 0, 0);
  strip.show();
  delay(3000);


  strip.setPixelColor(0, 35, 25, 0); // callibrate the value of a tensioned muscle, while a yellow led is on.
  strip.show();
  delay(500);
  calHi = (analogRead(pad));
  delay(500);
  strip.setPixelColor(0, 0, 0, 0);
  strip.show();
  delay(500);

  drempel = (calLow + calHi) / 2; // here the threshold value is calculated.
}

void loop() {
  ledOn = 0;//initially, the led does nothing.
  reading = analogRead(pad);

//if the sensor value is higher than the treshold, various readings will take place to see if either one short/two short/
one long input is provided.
  if (reading > drempel) {
    delay(100);
    for (int i = 0; i < 100; i = i + 2) {//this is to make sure that the first block wave is measured and antisipated on how
long the user intended it to be.
      reading = analogRead(pad);
      delay(5);
      if (reading < drempel) {
        break;
      }
    }
    reading1 = analogRead(pad);
    delay(75);
    reading2 = analogRead(pad);
    delay(75);
    reading3 = analogRead(pad);
    delay(75);
    reading4 = analogRead(pad);
    delay(75);
    D1 = ((reading1 + reading2 + reading3 + reading4) / 4); //for the second part of the block wave an average is
calculated.

    reading5 = analogRead(pad);
    delay(75);
    reading6 = analogRead(pad);
    delay(75);
    reading7 = analogRead(pad);
    delay(75);
    reading8 = analogRead(pad);
    delay(75);
    D2 = ((reading5 + reading6 + reading7 + reading8) / 4); //for the third part of the block wave an average is calcu-
lated.

    Dtot = (D1 + D2) / 2;// a total average is calculated of all readings.

  //based on logic gates the system determines how to interpret the given input.
    if (D1 > drempel && D2 > drempel && Dtot > drempel) {
      ledOn = 1;
    }
    if (D1 < drempel && D2 > drempel) {
      ledOn = 3;
    }
    if (D1 < drempel && D2 < drempel && Dtot < drempel) {
      ledOn = 2;
    }
  }

  if (ledOn == 1) {////////////////////////////////////////////red
    strip.setPixelColor(0, 50, 0, 0);
    strip.show();
    delay(500);
    strip.setPixelColor(0, 0, 0, 0);
    strip.show();
    delay(500);// an extra delay is added so that the system will not register a single short muscle tention (green)
unintentionally right after one long one (red).
  }
  if (ledOn == 2) { ////////////////////////////////////////////green
    strip.setPixelColor(0, 0, 50, 0);
    strip.show();
    delay(500);
    strip.setPixelColor(0, 0, 0, 0);
    strip.show();
  }
  if (ledOn == 3) { ////////////////////////////////////////////blue
    strip.setPixelColor(0, 0, 0, 50);
    strip.show();
    delay(500);
    strip.setPixelColor(0, 0, 0, 0);
    strip.show();
  }
}
```