Concept development of a minimalistic robotic glove meeting the needs of people with cervical spinal cord injuries

Olivia Wiaczek and Julia Uhlhorn Bardis

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MASTER THESIS

tendo
for people, not symptoms

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Department of Design Sciences
Faculty of Engineering LTH, Lund University
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Supervisor: Per Liljeqvist
Co-supervisor: Sofie Woge
Examiner: Håkan Eftring

Abstract

Living with a cervical spinal cord injury entails many limitations in everyday life, not least when it comes to something as simple as gripping an object. Individuals with a cervical spinal cord injury can modify or use specially adapted everyday objects to make gripping them easier. It is important to customize the objects based on the individual's abilities and limitations. Tendo is a company that has developed a soft robotic glove intended to help the user grip different objects and thereby instead reduce the needs for adapting the objects. The objective of this thesis was to redesign Tendos assistive robotic glove and develop a design concept based on the end users' needs and wishes.

This study involved conducting interviews and questionnaires to gather information on the needs and wishes from users' as well as the challenges and limitations that need to be addressed in the development of a robotic glove. Based on the gathered information a concept for a robotic glove was defined and tested, through an iterative development process.

The final concept consists of a minimalistic glove that helps the user achieve their biggest desire - greater independence. The design of the glove is tailored to activities of daily living and in doing so, helps the user become more self-reliant. Our findings highlight the importance of customization options in the design of this type of assistive device to meet the user's needs and preferences based on their individual abilities and limitations.

Keywords: Cervical spinal cord injury, Robotic glove, Assistive technology, Activities of Daily Living, Rehabilitation engineering

Sammanfattning

Att leva med en cervikal ryggmärgsskada innebär många begränsningar i vardagen, inte minst när det gäller något så simpelt som att greppa ett objekt. Personer med cervikal ryggmärgsskada kan modifiera eller använda speciellt anpassade vardagsföremål för att göra det enklare att greppa dem. Det är viktigt att anpassa föremålen utifrån individens förmågor och begränsningar. Tendo är ett företag som har utvecklat en mjuk robothandske avsedd att hjälpa användaren att greppa föremål och därmed minska behovet av att anpassa föremålen. Målet med detta examensarbete var att designa om Tendos robothandske och utveckla ett designkoncept baserat på slutanvändarnas behov och önskemål.

Denna studie innefattar genomförande av intervjuer och frågeformulär för att samla information om användarnas behov och önskemål samt utmaningar och begränsningar som behöver hanteras vid utvecklingen av en robothandske. Baserat på insamlad information definierades och testades ett koncept för en robothandske, genom en iterativ utvecklingsprocess.

Det slutgiltiga konceptet består av en minimalistisk handske som hjälper användaren att nå sin högsta önskan - större självständighet. Handskens design är anpassad till vardagliga aktiviteter och på så sätt hjälper användaren att bli mer självständig. Våra resultat lyfter fram vikten av anpassningsalternativ i utformningen av denna typ av hjälpmedel för att möta användarens behov och önskemål baserat på deras individuella förmågor och begränsningar.

Nyckelord: Cervikal ryggmärgsskada, Robothandske, Hjälpmedel, Aktiviteter i dagliga livet, Rehabiliteringsteknik

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Lund, May 2023

Olivia Wiaczek and Julia Uhlhorn Bardis

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List of acronyms and definitions

ADL	Activities of daily living
C4, C5, C6, C7	Vertebrae numbered 4,5,6,7 on a cervical level of the spine
DIP	Distal interphalangeal joint
Distal	Situated distant from the body's center of mass
Dorsal	The back of a body segment
Lateral	Out to the side, away from the midline of a body segment
MCP	Metacarpophalangeal joint
PIP	Proximal interphalangeal joint
Proximal	Situated close to the body's center of mass
PVC	Polyvinyl Chloride, thermoplastic rubber-like material
Two-component silicone	Two components (base material and curing agent) mixed to obtain a silicone with desired cure and properties

1 Introduction

This chapter presents the background, the current product, mission statements and delimitations for the project.

1.1 Background

Tendo is a design driven Nordic company within the field of medical technology, focusing on development of a robotic medical aid for people with gripping limitations. The system consists of a glove, a sensor unit and a control unit. The purpose of the soft robotic glove is to assist the user in gripping activities. In this project, we will examine the user group's perspective on this specific type of assistive device. Based on this information, we will then develop a new concept for Tendos glove that better meets the users' needs and preferences.

The first spark of Tendo was set by their founder as a master's thesis project with the hopes of assisting people with gripping limitations caused by e.g., rheumatism, stroke or old age. Since then, the company has developed and shifted focus to a more specific user group with the aim of providing grip assistance in activities of daily living for people with cervical spinal cord injury (C4-C7 level) [1]. The result is a soft robotic glove that assists the user in gripping motion using an artificial tendon system. In 2023 their first product OneGrip is set to reach the market.

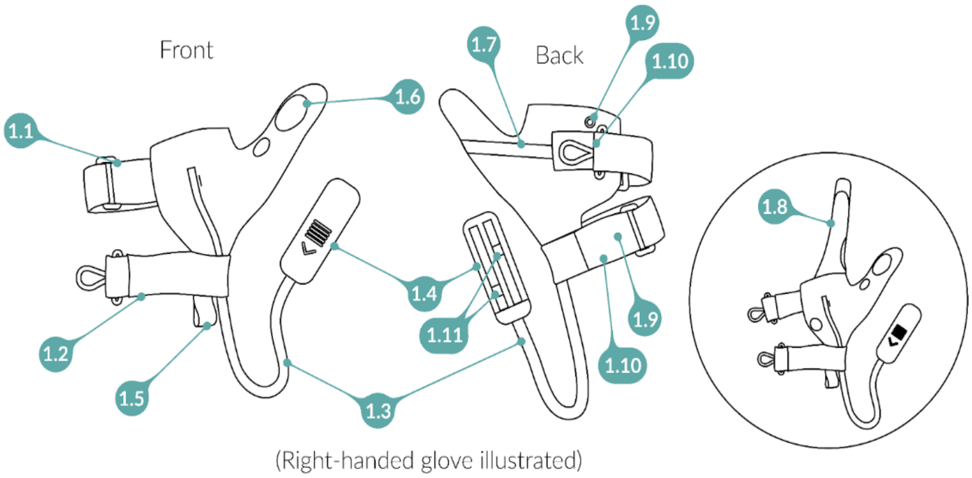
There are different assistive devices on the market today for people with limited grip, these are essentially limited to assist in one specific situation. It can for instance be a special holder for cutlery or a pen. Kitchenware and other at-home-gear may also be specially designed in order to facilitate everyday activities. However, this still leaves gaps where the user remains limited in activity and can cause a feeling of isolation. What happens for instance when the user is leaving home, to environments not specifically adapted? Of course, some aids may be possible to carry with you, but a special aid for every potential activity may become many in total and at the end impractical. This is where Tendo's product contributes to a more general solution, for several activities with just one device. With Tendos OneGrip the user can grip several objects without the need for those to be specially adapted. As long as the user is carrying the product no more aid is needed in order for gripping. In this perspective one can say that the user with this one product can adapt to the surrounding world, instead of having it the other way around.

1.2 One Grip – The current solution

Tendos first product, OneGrip, is an active orthosis device that enables individuals with limited hand function to perform a range of activities of daily living (ADLs) with greater independence and ease. OneGrip, as shown in figure 1.1, is intended for people with reduced gripping function following a cervical spinal cord injury in the C4, C5, C6 and/or C7 vertebrae - complete or incomplete. The device is worn on top of the user's own hand throughout the whole day, and actively helps the user to grasp, hold and let go of objects following the user's movement. The device assists the user in the pinch grip. To gain benefits from the product the user needs to have movement in at least one arm but minimal to none grasping/hand function in combination with the ability to lift at least one wrist. Depending on the user's own degree of delimitation a personal assistant could assist in the process of taking on and off the orthosis as well as in some of the product's functions.

Figure 1.1 The current solution, OneGrip [1].

The glove and its associated parts are shown in figure 1.2. A motor unit produces the force and pulls the artificial tendons connected to the motor unit, 1.4. These tendons run through small plastic tubes and connect directly to the glove. The purpose of these plastic tubes is to minimize friction between the fabric and the tendon, keep the tendons in place and to protect the tendons from wear and tear. The end points of the tendons are attached into the fabric at the palm side and the back side of the hand. The glove has two straps, 1.1 and 1.2, one for keeping the glove in place and the other for keeping the tendon cord, 1.3 in place during movement in the wrist. These straps have pull loops that facilitate for the user to tighten the strap and the user can insert a finger into the loop, or bite on it, and then pull to tighten. A grip pad is placed on the thumb, 1.6 to maximize friction between the hand and an object that is being grasped. The bend sensor is placed on the upper side of the glove,1.9 and is connected to the motor unit by a separate cord. The bend sensor activates the system upon registration of the user's wrist movement, utilizing the tenodesis grip. OneGrip mainly exerts flexion and extension in the thumb, however, to enable the right grip, the thumb needs to be placed in a suitable position of opposition. To enable this an abduction adjuster (elastic band), 1.7, is placed on the back side of the glove. There is a possibility to attach an additional part to the glove for the index finger, 1.8 to facilitate locking the index finger in a bent position to generate a more proper pinching grip [2].



1.1	Palm Strap
1.2	Wrist Strap
1.3	Tendon Cord
1.4	Glove Connector A
1.5	Pull Loop
1.6	Grip Pad
1.7	Abduction Adjuster
1.8	Index Finger Splint
1.9	Sensor Snaps
1.10	Sensor Slot
1.11	Sliding Connectors A

Figure 1.2 Detailed description of OneGrip and its associated parts [2].

1.3 Mission statement

The objective of this project is to redesign OneGrips glove to enhance its functionality, usability and aesthetic appeal following the users' needs and wishes. We will conduct user research to gain insight of the users and develop design concepts that address their needs. Our goal is to create a design concept that not only provides good grip assistance but also promotes independence, comfort and convenience for individuals with limited hand function. We aim to design, develop and prototype in an iterative way throughout the project and formulate recommendations for further development. Through this project we hope to contribute to Tendos mission of improving the quality of life for individuals with disabilities, through innovative assistive devices.

1.4 Delimitations

In this project the focus was on the users, their needs and their experiences of assistive devices. At first the intention was to build a functional prototype, with respect to the gripping motion, that could be connected to the remaining parts of Tendos product i.e., artificial tendons and motor unit. Unfortunately, it was not possible due to limited time and resources. Additional delimitations are stated below.

- In this project we have focused on the development of a concept for the glove and its associated parts. Mechatronic systems will not be overseen.
- All user tests are performed by and on the authors, unless stated otherwise.
- The prototypes are proof-of-concept and not a finished product by Tendo.
- The driving system and motor unit used in this development will be the same as in the current system.
- The activation principle of the product will be the same as in the current system. Although the new design is not limited to the design of the current sensor.

1.5 Work distribution

This thesis has mainly been carried out through collaborative work, thus both members participated actively in research and development of the concepts. Exceptions for the CAD constructions and 3D prints that were constructed and manufactured by Olivia Wiaczek. Sketches of the full glove iteration and final concept sketches were done by Julia Uhlhorn Bardis.

2 Theory

This project required certain knowledge regarding the anatomy of the human spine and hand, and the report thereby includes some terms related to this area. In order to get an overview of this content, the essentials are presented below.

2.1 Spinal cord injury

Spinal cord injury can be a very serious condition that has a significant impact on a person's life. Injuries to the spinal cord can be caused by a variety of factors, such as traumatic accidents, falls, or sports injuries. According to the World Health Organization, globally around 250,000 to 500,000 people suffer a spinal cord injury each year [3]. A cervical spinal cord injury can cause paralysis in a large part of the body including all limbs. When an injury occurs at the C4-C7 level, as seen in figure 2.1, it affects the upper and lower extremities of the body, as well as the torso resulting in a so-called tetraplegic injury. An injury located further down on the spinal cord might result in paralysis in the lower parts of the body and legs, called paraplegia. The specific effects of a spinal cord injury at the C4-C7 level depend on the severity of the injury and the exact location of the damage [4]. In general, injuries at this level can cause weakness or paralysis in the arms and legs, as well as difficulty breathing, speaking, and swallowing. The amount of damaged nerve fibers can vary between spinal cord injuries, everything from a few fibers to nearly all of them throughout the site of injury. There is hence a classification of spinal cord injuries into complete and incomplete injuries. If an injury is incomplete some signals can still transmit through the spinal cord, which may manifest as some remaining sensory function and/or some control of muscle activity below the site of injury. Conversely, sensory and motor function is lost in the case of complete spinal cord injuries due to the absence of nerve communication below the injury site. [4:5]

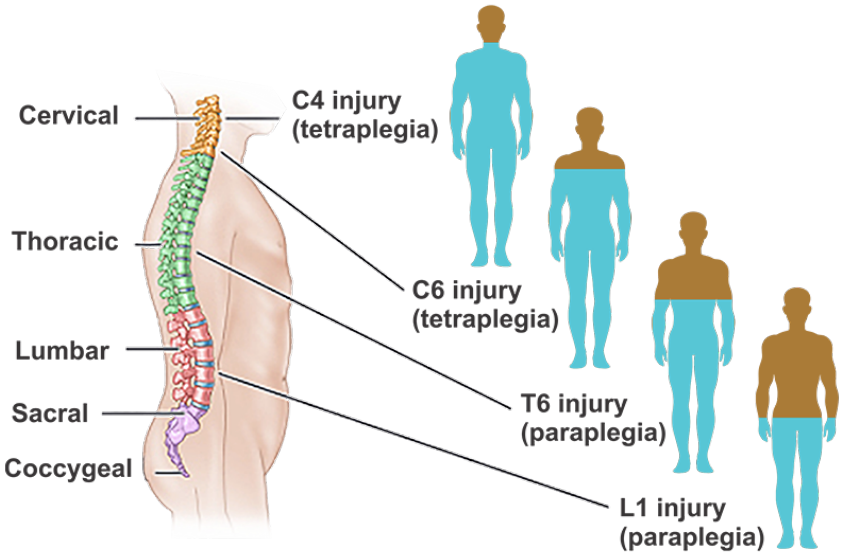


Figure 2.1 The human spine. [6]

2.2 Hand anatomy and topical terminology

There are some anatomical terms of location that will be used in this project. Proximal and distal are terms respectively defining if a segment is close (proximal) or distant (distal) from the body's center of mass. Frontal and dorsal are referring to the front (frontal) and back (dorsal) of a body segment. Moreover, medial and lateral implies how close something is to the midline of the body segment, where medial is closer to the middle and lateral out to the side [7].

The human hand has four fingers and one thumb and consists of a total of 27 bones [8]. There are 8 small bones of the wrist and then each finger has a metacarpal bone and phalanges. The fingers have 3 phalanges each whereas the thumb differs and only has two. The thumb is of primary importance for the function of the hand, much due to its ability of opposition movements where the trapezium bone, at the base of the thumb, constitutes a crucial piece. The metacarpal bones and proximal phalangeal forms the metacarpophalangeal joint (MCP). In the fingers, there is then a proximal interphalangeal joint (PIP) between the proximal and intermediate phalanges as well as distal interphalangeal joint (DIP) between the intermediate and distal phalanges. The thumb on the other hand, only has the MCP and DIP joints [8]. A visualization of the bones and joints can be seen in figure 2.2.

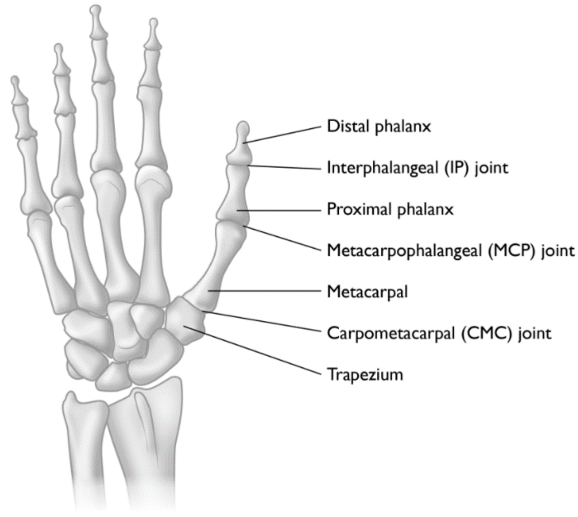


Figure 2.2 Anatomy of the hand [9].

2.3 The grip

The possible movements of the thumb are flexion, extension, abduction, adduction, opposition and reposition, as can be seen in figure 2.3.

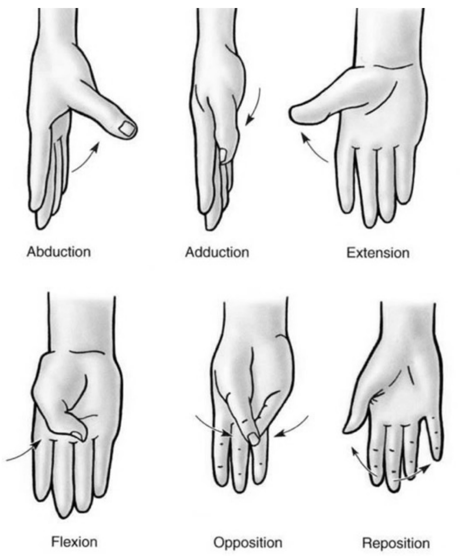


Figure 2.3 Movements of the thumb [10].

The tenodesis function is a useful tool for many people with tetraplegia who maintain wrist motor function, despite lack of full active functionality in the fingers. It is a passive grasp based on the following progress; When the extensor muscles in the wrist and forearm are contracted, moving the wrist to an extended position, the finger tendons are passively pulled towards the wrist. This is generating a bending moment of the fingers into the palm, see figure 2.4, which advantageously enables grasping in the paralyzed hand [11]. The grip can be divided into two kinds; one performed passively by the whole hand due to the shortening of the flexor muscles in the fingers (digits 2-5), and the other a lateral pinch grip created passively due to shortening of the flexor muscles in the thumb. The limited elasticity in the muscle fibers of the hand and the connective tissue elements composing the muscle-tendon-bone unit is thus crucial for the passive mechanism of the grip.

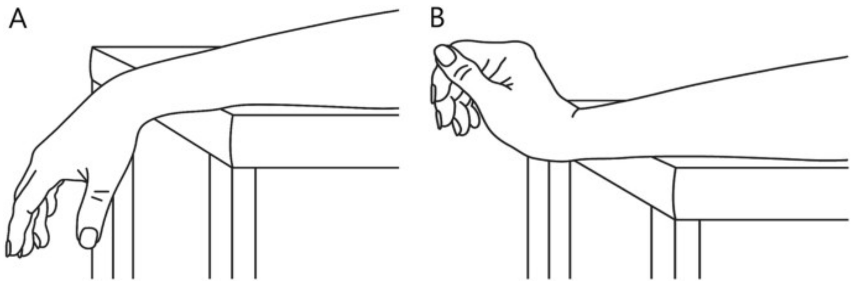


Figure 2.4 The tenodesis function [12].

The current product developed by Tendo is assisting the performance of a lateral pinch grip by utilizing the tenodesis function amongst the users. As figure 2.5 shows, it implies holding an object between the palmar surface of the thumb and lateral surface of the index finger. The thumb thus moves between flexion and extension, but also needs to be in a position of suitable opposition. This type of grip is categorized as precision grip rather than power grip and is commonly used when gripping smaller objects [13]. Figure 2.5 below illustrates what the tenodesis function and resulting lateral pinch grip may look like in reality, performed by a person with tetraplegia [14].

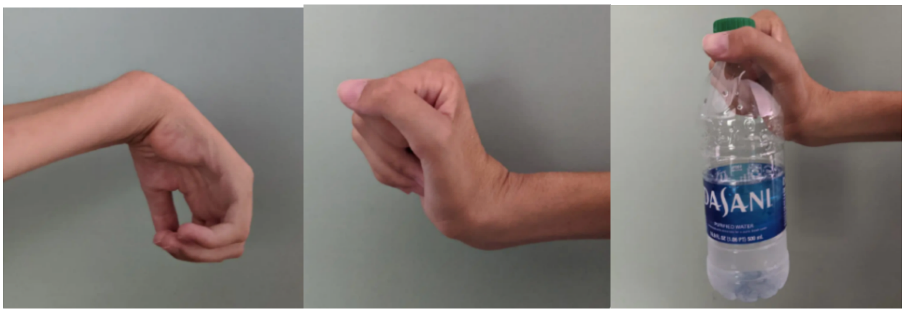


Figure 2.5 The tenodesis function [14].

The extent of impaired hand, arm and gripping function with people who have a cervical spinal cord injury is highly individual. All patients go through physiotherapy to work with their hand and arm function, some may learn the tenodesis grip and others may do well without it. The benefits that the tenodesis grip provides for many people with tetraplegia, make learning to master this grip a significant part of their recovery. Other ways to gain better hand, arm or gripping function is through reconstructive surgery, but far from all patients that are offered this choose to go through with it [15]. Living with a spinal cord injury can be challenging, but with proper care, support and aids, individuals can live full and fulfilling lives [4].

2.4 Rehabilitation engineering

In the area of rehabilitation engineering, the needs, wishes and dreams of the human make out the fundamentals in the design development. It is a cross-disciplinary field with the focus on people with disabilities. The field brings together diverse areas such as technology, medicine, social science and humanities. The main goals in rehabilitation engineering and design are to ease and comfort the individual, the end user. It is a unique field that combines engineering with understanding of humans and the challenges that come when faced with a disability. A field where the technology is adapted to the needs of the people, and not the other way around. The results of research in this field are not limited to specific prototypes or product development, but also include new insights into the needs, desires, and dreams of people with disabilities, which can be utilized in development of other products. In this field the user's satisfaction is the most important measure of success [16].

To gain a fruitful design it is of great importance to involve the users in the development process. In addition, it is important for the developer to gain a deep understanding of the users, their needs and wishes as well as the context of the product. Utilizing the philosophies in human-centered-design, as described below, is a way for the developer to reach these insights and understandings in the development process [16].

Once an idea has been developed it can be fruitful for the future development to let users engage and interact with the generated ideas and concepts. In this way a user can imagine future usage of the product and in such a way also find strengths and weaknesses with the design that may be addressed early in the development process. This can be done with mock-ups, prototyping, or videos of the design. Showing prototypes to intended users and include the users in the development of these prototypes comes with a lot of benefits. The developers can not only gain valuable information about the concept itself, but it can also be a way of discovering common patterns in users that generate new hypotheses and design principles [16].

3 Methodology

The overall method for this project was an iterative design process with a user centered focus. In the following part, a brief description of the course of the project, with included methods and philosophies, is presented. Detailed descriptions of specific methods will be accounted for later in the report, in the respective phases of which the methods are included.

3.1 Double diamond

The overall approach of product development in this project was mainly based on the Double Diamond Design Process. This design methodology was developed by the British Design Council and constitutes a framework for innovation by providing designers as well as non-designers with a comprehensive description of the design process, presented in a clear visual way [17]. Going more into detail in the framework and each of its phases, a lot of inspiration was additionally gathered from the product development process presented by Ulrich and Eppinger [18], as well as some of their presented methods. The principles of Human Centered Design [19] have also been present in the design process of this project.

Figure 3.1 illustrates the Double Diamond Design Process. The two diamonds can be considered to have different areas of focus. The first diamond focuses on the problem, to identify as well as understand and define it and its extent, whereas the second one represents the actions of problem-solving and generating solutions to the defined problem [20]. The diamond shapes represent the duality of divergent and convergent thinking throughout the process. Divergent thinking implies investigating an issue to a wider or deeper extent, to think freer and explore multiple perspectives of the problem area. This way of thinking often has a non-linear appearance. The expansion of thinking is illustrated by the opening first half of the diamond, starting at one point alone and opening up and embracing a wider area. In a reversed way, convergent thinking signifies a more focused and linear approach complementing divergent thinking by scoping a project down to something more concrete and manageable. It can be seen as extracting the key findings from a comprehensive exploration and is illustrated by the closing second half of the diamond where the lines again meet at one point. The development process described by the Double Diamond consists of four main phases, ranging from initial problem to final solution; Discover, Define, Develop and Deliver. [17:20]

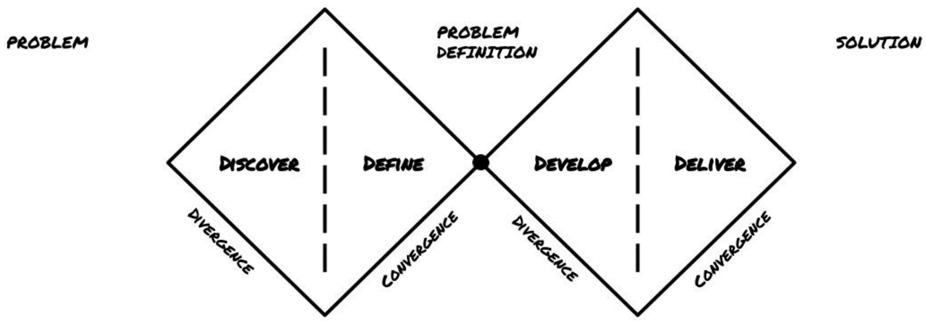


Figure 3.1 The Double diamond process.

Discover

As mentioned, the initial diamond targets the problem itself before aiming for a solution. The first step of the first diamond, Discover, is the divergent approach of exploring and identifying the problem to gain insight and understanding of the situation and the people affected. Moreover to distinguish why the problem is, and the affecting factors in the surrounding [20:21]. A complete perception of an issue is important in order to avoid making insufficient or inaccurate assumptions, further reducing the risk of sub-optimized solutions that do not meet the user's wishes and expectations. The aim of this phase is commonly achieved by planning and exploratory research. [17:20:21]

Define

The Defining phase is about the converging methodology, taking the findings from the Discover phase and analyzing and organizing this data in order to narrow them down to define the problem statement, needs and requirements as well as objectives for the sequent part of the process. In comparison to the initial problem, going into the design process, the defined problem statement will have more support and context to it. This is very beneficial and will facilitate when approaching the problem-solving actions in the second diamond. The practice of linking research data to design ideas is significant for this process, and termed Design Synthesis. [17:20:21]

Develop

The step of the develop phase implies idea generation influenced by the outcome of the previous diamond. The aim of this phase is to produce feasible solutions for the defined problem. In the same way as the research is carried out divergently, the approach is comprehensive with possibilities in problem solving. In this phase extensive concept generation is commonly included with activities such as sketching. This can be followed by prototyping of potential solutions, starting off with low-fidelity prototypes which can subsequently be developed into more advanced ones. Part of this is also testing and evaluating various solutions in between. [17:20:21]

Deliver

The intention of this phase is to validate the solutions originating from the previous stage, to test them and evaluate them in order to make a final downscaling of the range of working solutions. In other words, to weed out the proposed solutions that don't work or meet desired characteristics. To home in on the remaining solutions may require iterations of adjustments and refinements in order to improve the design so that it approaches the end goal of a final product. [17:20:21]

The process displayed by the Double Diamond is however not meant to be linear [17]. When working hands-on in the various phases, underlying problems may be discovered requiring going back and redoing some of the previous steps. Iterations are thereby principally always needed, and the actual course of events thus becomes unique for each project.

3.2 Our implemented method

As previously mentioned, the implementation of iterations, as well as what tasks are included in each phase, varies between projects. In figure 3.2, an attempt has been made to illustrate the progress of the current project. In the Discover phase, research was made in terms of a literature study, market analysis, expert and user interviews, observations and questionnaires. The outcome of these steps then constituted the fundament when establishing needs, requirements and sequent objectives in the Defining phase. The phase of Development was the largest phase, starting with concept generation and evaluation before going into prototyping and concept definitions. The prototyping contained low-fi prototyping as well as mid-fi constructions and 3D-prints, with subsequent iterations of ideation, prototyping and testing until a preliminary final concept was achieved and evaluated by potential users. The project then contained the first steps of the Deliver phase, covering some refinements leading up to the final concept, based on the results of the previous phase.

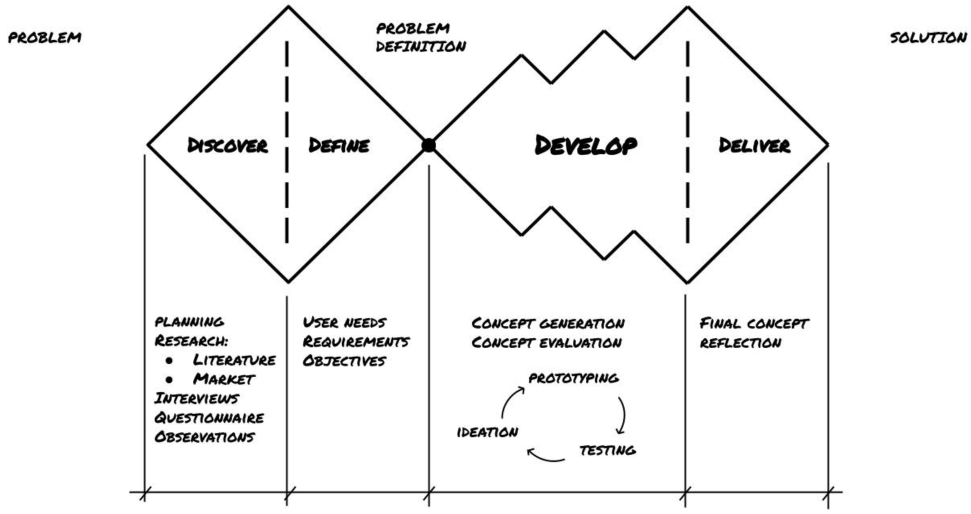


Figure 3.2 Our implemented development method.

3.3 Human-Centered design

Human-centered design is of great value in the context of designing medical aids. It is particularly important as the stakes are high thus the medical device is designed to improve not only the health and well-being of the user but also in many cases their life quality. As human centered design prioritizes the needs and experiences of the users, this approach aims to ensure that the best is made out of the human-machine interface and that it meets the needs of the users [19].

As this methodology highly involves the users in the design process, the designers gain a valuable insight of the users' needs, wishes as well as limitations. For the design of medical aids this is of great importance as all individual users have different needs for the product. Thus, this method enables the design of a product that is easy to use, effective and better understands and meets the users' needs.

This method can also help the designer to better understand specific limitations for the user that can potentially be harmful or result in any risk. These aspects can then be taken into consideration for development of a product with reduced risk and understanding of potential usability issues [19].

The main phases of human-centered design are:

- Inspiration – Empathizing with the users to understand their need, wishes as well as limitation.
- Ideation – On a base of inspiration great ideas are born.
- Implementation – The bringing of ideas to life.

3.4 Universal Design

Universal Design is an approach that is based on the idea of an inclusive design rather than an exclusive, and that the design should be able to meet the needs of a wide range of users. By creating products, environments and systems that are accessible, understandable, and beneficial for as many people as possible, regardless of their age, size, ability or disability and by considering the diverse needs of potential users through the design process, a universal design can be created. [22]

Universal Design is based on these seven principles:

1. Equitable Use
2. Flexibility in Use
3. Simple and Intuitive use
4. Perceptible Information
5. Tolerance of Error
6. Low Physical Effort
7. Size and Space for Approach and Use

A well-designed product, where accessibility and usability has been considered for in the development process can result in a more usable, safer, and a higher effectiveness of the product, and thus provide greater independence for the users [23].

3.5 Triangulation

The choice to combine methods of different character throughout the research process can be justified by the utilization of methodological triangulation. Triangulation is a universal approach examining outcomes of interconnected research questions by how they appear in conjunctions or disagreements as well as complementarity. In other words, the term triangulation is principally describing the comparison of collected qualitative data. The outcomes may for instance be acquired from various methods, sources, theories, perspectives, or researchers. There are four types of triangulations, where methodological triangulation is one. It implies using more than one methodology to collect data. The application of triangulation is increasing the credibility and validity of convergent findings and their entailing conclusions. [24:25]

4 Discover

During the Discover phase we began with a literature search on state of the art, reviewed studies related to the user group's experiences of living with their injury and sought for other relevant similar solutions on the market. We proceeded to delve deeper into the users themselves and conducted interviews, questionnaires, and observations to understand them, their needs, and their desires. Finally, we proceeded to learn more about Tendos product, and any potential challenges associated with it through interviews with individuals at the company.

4.1 Methods

To develop a successful solution, it is important to gain understanding of the context, the environment where the product will be used and foremost understand the users' needs and wishes [26]. There are different tools available to assist in this research phase, for example questionnaires, interviews, and observations. These methods are described below.

4.1.1 **Questionnaire**

Surveys are a well-established method for user research utilized to collect demographic data as well as opinions of potential users. An online survey is advantageous in that it can be done when it best suits the respondents themselves and, in an environment, where they feel safe and at ease. The method was also chosen in order to reach out to potential users and collect data in a relatively quick way without burdening the respondents to a greater extent. Thereto, online surveys enable reaching users living in a remote location that can thus not participate in executions on site [25].

Three potential users were identified with the help of Tendo and our supervisor and were invited to participate in an online questionnaire. Two of these individuals were also invited to participate in interviews later on. A Google Form questionnaire was e-mailed to them, and the individuals were asked to respond to 14 different questions. The aim with the questionnaire was to obtain answers on more general questions about the users, their involvement in assistive devices as well as about the most important characteristics and attributes of these.

The respondents were given information about the current project as well as instructions on how to complete the survey. Initially, the form included questions regarding basic demographic information such as gender and age. They were then followed by questions about their experiences and current situation, how long they have had their spinal cord injury, what their hand function is like as well as situations they find challenging in their everyday life. The last part of the form concerned assistive aids, which solutions they use today and what is important to them regarding the design of hand aids specifically.

The questions asked were of quantitative as well as qualitative nature and combined closed questions with more open-ended ones. The response formats included multiple-choice questions, rating scales as well as shorter text answers. The aim of this arrangement was to gain pure quantitative statistics and at the same time give the respondents room to develop their answers, which can give greater insight and a more detailed picture of their situation and their feelings towards it. The answers were then analyzed before the interviews in order to provide inspiration for new interview questions, but also to deepen and ask follow-up questions within the areas the questionnaire touched upon.

4.1.2 **Interviews**

An interview is a meeting with users with the aim of finding experiences, thoughts, motivations and behavior in relation to the product. It can also be a way to gather information from experts. Experts related to the context of this project include the developers of the product. As the product is yet not on the market the insights and knowledge with the developers and people associated with the project is of great value. Interviews can give valuable information in different stages of the process. In the beginning of a project information about the usage and positive versus negative aspects of the product can be gathered. Later on, in a project the interview can be used as a way of gathering feedback on a developed concept [26].

Based on the access to, and the possibility of being able to meet potential users, the plan during this project was to work more closely with two users. These two users, one male and one female, were interviewed in a semi structured way that led up to a 2 hour long open discussion. One interview was conducted online with video and the other in person in the individual's home. The purpose of these interviews was to learn more about the individual's life situations and what their everyday life looks like, their needs and desires. Both users had prior been in contact with Tendo in the company's development phase, and were hence familiar with their product, therefore additional questions about their thoughts and experiences of the product were asked.

To further understand and gather in depth qualitative insights of the challenges and problems with the current product, we conducted two interviews with people closely working with Tendos product today. These two interviews were semi structured with open questions related to the functionality, aesthetics and development of the current glove. We also discussed potential improvements, as well as needs gathered directly from both the company and indirectly from the potential users, passed on through employees who had prior close contact with the users.

The interviews at Tendo aimed to establish the following:

- Limitations of the current product
- Users' limitations
- Future hopes and wishes for the product

4.1.3 **Observations**

Observations are relevant in research for product development as it enables the developer to observe the user in its most natural environment providing a more accurate picture of how people interact in real-world situations. The observation is done without intervention or manipulation of the subject. This powerful tool can help identify areas of further investigation and better understanding of the users' needs [26]. Much information is provided by the doing, the actions and different situations. And some people may have difficulties expressing their needs in words, thus observations may be complementary in these situations.

In this project, we were working with a specific group of intended users, that in addition make out a small representation in the society. As this intended group of users is relatively small, we chose to seek other forms of observations than strictly physical in person. We therefore chose to turn to YouTube. With the help of the millions of videos posted on YouTube we found a variety of people with spinal cord injuries who share and show their everyday life. These YouTube videos were then used as the basis for our observations.

4.2 Results

Below are the most important outcomes from the project's initial research. First, the findings from the literature study are presented, followed by summaries of the interviews and questionnaires conducted with users as well as experts at the company.

4.2.1 **State of the art**

Exoskeletons for the hand have so far been designed in two different ways, one type is the more rigid skeleton built up by rigid linkages placed over various parts of the hand and fingers, and the other one is a softer exoskeleton more commonly called an exosuit or soft robotic suit. The rigid link-based concept is the one that has been around the longest and thereby perhaps, at least until today, is most associate with the term exoskeleton. The included word skeleton also implies some kind of framing structure. However, some of the more recent research on developments of wearable robots has focused on solutions for a less restrictive device, like the soft robotic suit made with more compliant materials. Soft robotic suits can be described as more clothing-like, enfolding the body and acting along the muscles. Instead of making use of an external load-bearing structure, transmitting reaction forces, soft robotic suits utilize the body's own structural integrity. In these terms one can say that they constitute external muscles rather than an external skeleton. [27]

4.2.1.1 Advantages and challenges with rigid linkages and soft robotic suits

Rigid link-based and a soft suit both have their advantages and challenges, which each can be of various significance depending on the situation and intended use of the device. Below are some of the stated pros and cons of each concept, expressed in literature including state of the art research.

One of the main advantages with a rigid link-based exoskeleton is that the force transmission from the device to the body is more efficient. If the linkages are working well and can move smoothly in relation to each other with low friction, the losses of force are small. In this case, the device may be easy working and entail increased control. Another benefit with the link construction is that it enables adjustments of links separately. This may become relevant when there is a need for sizing the frame according to the user's measurements. If the length or angles of certain parts must be adjusted in order to better fit a person, a link can be replaced with another that is a better fit without having to replace the whole construction. The same applies if a link is broken. Thereto extra links/elements can be added. However, changing the design of links or the structure they build up, can cause changes in behavior which may depart from the intended use. This is thereby important to keep in mind and verify when making changes. When designing rigid linkages, it is very important to ensure they align carefully with skin and joints, for safety reasons and comfort as well as for efficient force transmission to the wearer. There are thus great demands on the shape of links and may call for personalized design, which could entail more steps in the manufacturing process. [11: 28: 29]

The main advantage of a soft robotic glove is the increased compliance as well as more accessible comfort. In many cases there are also greater possibilities to create a light-weight solution facilitating movability and the soft and compliant properties can moreover facilitate the procedure of taking the glove on and off. Due to the compliant characteristics, it is easier to make a suit fit the anthropometry of the current user, hence the customization is easier. In addition, many soft materials can be stretched out to a certain extent leaving some margin for small differences in measurements between user and glove, further implying that adjustments are not needed within this range. Beyond the range there is however a need for adjustment where it is not possible to replace only a part of the glove. At the same time as the compliance contributes to several beneficial aspects it may also increase the nonlinearity, and thereby complexity, of the system making it harder to control. It can be harder to obtain an even distribution of forces from the wires to the wrist and fingers, and thereby the suitable amount of force to each joint. The elasticity of the material can also cause unintended behavior if the stretched-out material changes the trajectories of the tendons, and there will be weaker force transmission with larger losses. [11: 28: 29]

4.2.2 **Market analysis**

A variety of soft robotic gloves are available on the market today. Many of these focus mainly on rehabilitation for stroke patients, for neuromuscular rehabilitation or other kinds of impairment that result in impaired grip strength. Soft robotic gloves meant for assistance in ADLs are on the other hand limited. Besides from Tendos OneGrip there are only two similar products available on the market today. These are:

- Neofect - Neomano Robotic Grasp Assist
- Bioservo – Carbonhand

Figure 4.1 Neofects Neomano glove [30] and Bioservos Carbonhand [31].

These two robotic gloves are for patients with impaired strength and meant to be used in daily activities. Both these products have several common nominators when looking specifically at the glove design. Both products are made of a fabric-based material and support two or more fingers. The products cover a big portion of the hand, with the Neomano having a slightly bulkier design due to its leather details. Both products describe a similar supportive force up to 20N. The Carbonhand from Bioservo uses pressure sensors whereas the Neofect glove is controlled by a remote control [30,31]. Overall the different products do not differ much in the first glance at the design. The big difference lay in the control system and activation. The functionality is yet to be discovered as we did not have any data on the core function and gripping sensation provided by these two specific gloves.

4.2.3 **The experience of those with a spinal cord injury**

In terms of rehabilitation technology and in order to understand the possible contribution of a product as OneGrip by Tendo, it is necessary to gain insight and understanding about how people with a cervical spinal cord injury perceive themselves and experience their quality of life.

4.2.3.1 Independence

To suffer a spinal cord injury changes a person's life in several ways. The change may affect the view of oneself, the value seen in one's own eyes but perhaps also the experience of valuation in the eyes of others [32]. In order for people to maintain a sense of value, independence is an important aspect. Manns and Chad [33] investigated components of quality of life for people with spinal cord injuries and presented "physical function and independence" as one of the nine established themes composing it. The theme mainly implied the ability of people to perform physical tasks within their present limitations, without expending so much energy that it causes exhaustion for the remaining day. It could refer to mobility in various ways, but also autonomy in ADLs. In people who have sustained a spinal cord injury, independence is a driving force and motivation and several have expressed the longing to not have to ask others for help as often [32]. Not having to wait in or rely on other people in one's surroundings brings greater freedom in everyday life. Many develop solutions to certain problems on their own, and these always aim to increase the perceived sense of independence, freedom and by that also empowerment.

4.2.3.2 Mental experiences and socialization

Increased physical independence may furthermore have a positive mental impact as well as strengthen the feeling of belonging to a social context. First of all, physical independence brings the possibility of spontaneity in everyday life. "Spontaneity" was also established by Manns and Chad as another one of the nine themes contributing to quality of life for people with spinal cord injury. It was communicated that being dependent on other people required a great deal of planning and that performing activities and tasks often took longer, which in turn reduced spontaneity [33]. Being more independent, for instance by having access to the right aids, would enable increased spontaneity and facilitate participation in social activities. Socialization is another important theme for life quality as social participation may promote the experience of strengthened identity and belonging as well as nurturing relationships.

4.2.3.3 Stigmatization

The presence of stigma, or the perception of its presence, may negatively impact the quality of life for people with spinal cord injuries. In this case stigma refers to the attitudes of the surrounding world towards people with spinal cord injuries, perceived by them as people with spinal cord injury. Some participants in the study of Manns and Chad [33] communicated that their experiences of stigma changed with time and adjustment to their new life, affecting them most within the first 2-3 years and then lessened. Important to bear in mind is however that the experiences and perceptions vary between individuals, and the impact of stigma may thus be greater for some people compared to others.

The presence of stigma is an important aspect to investigate and take into consideration during the design process. To examine the form in which the stigma appears to the users, in order to further discuss if there is anything in the design of the product that can counteract it. This also connects to the approach of universal design and the first principle of "Equitable use" specifically, where one guideline is to avoid segregating or stigmatizing any users [34].

4.2.4 **Previous user survey**

Sofie Woge did in depth user research when working on her master's thesis project, which later on resulted in Tendo [35]. However, the target group looked different at this time and aimed mainly at people affected by rheumatism, stroke, and elderly people with limited grip strength. The reflective answers gave valuable insight into the perspective of the target group and their view of the design. Extracted quotes could be divided into several design topics. One was the *Discreteness* of the final solution, where requests like not having to be reminded of the device and being able to hide the device under the shirt was mentioned. Another topic was about the *Comfort* of the glove, or more specifically the heat it could cause, mentioning that a full coverage glove would be too warm and sweaty. A lighter and more breathable solution was suggested. *Lightness* and *Hygiene* were other topics mentioned with requests for a solution that is easy to clean as well as light and discrete in its design in order to not be in the way when using the hands. The most important feature for a hand tool according to the responders was *Comfort* (receiving 37%) followed by *Airy and cool* (17%) and *Resistant to water and dirt* (15%). More features that were selected but received a lower percentage of responses were *Easy to put on/take off*, *Doesn't show/invisible* and *Small* mentioned in order of magnitude.

In addition to the questionnaire, Woge investigated the acceptance towards medical aids within the target group at the time. It was extracted that the stigmatization could be reduced by creating a product looking less like a medical device, thus not being a constant reminder of the situation. Designing a wearable device in a way that it becomes a natural part of the body could additionally make it easier to forget about, and by that reduce stigma as well as increase acceptance within the user herself. Another interesting aspect that emerged was how the ability of wearing the device at all times could contribute to acceptance. No need for adaptation or taking it off, may increase the likelihood of the device being used as well as enhance the user's acceptance of it. [35]

4.2.5 **Questionnaire results**

The respondents of the questionnaire were all in the age range of 41-65 years. Two people had lived with their injury over ten years at the time and one less than ten years. They all had reduced hand and grasping ability, but with some to moderate residual function.

Something made clear by the answers was that impaired hand function affected several situations in everyday life. Fine motor tasks were problematic to manage; to grasp, hold and turn small objects. Even for somewhat larger objects such as books and binders, it could be difficult to get a secure grip. One respondent simply answered: "It affects everything in my life". All three respondents, one female and two males, utilize the tenodesis grip in order to pick up and grasp objects such as keys, kitchenware, cutlery and the remote control. One common nominator was that the responders did not use any specific additional helping tools or products for gripping today. One respondent did however describe the use of loops, self-made out of cable ties or lace and add to object to facilitate usage. It was also clear that the comfort and fitting was higher ranked than the physical appearance of the device. The gathered results show that one big reason why people refrain from using an assistive device is more related to how well the device functions and how big it is to potentially bring along. When the respondent had the opportunity to give an additional comment about the concept design a desire was expressed for the aid to be easy to put on, provide good friction to the grip and not be too clumsy.

4.2.6 **Interviews with potential users**

Both interviewed individuals had limited gripping function and used the tenodesis grip as assistance in gripping situations and both had undergone reconstructive surgery to improve their hand function. Although they described the improvements from the surgery only sufficient on lighter gripping situations, there still is a lack of sufficient force to grip heavier things.

Both users described product features such as lightweight and small size as important in an assistive device, but the most important thing was the function itself. A well-functioning assistive device will most likely be used even if it has a design and appearance that does not fully appeal to the user. For an assistive device meant to be worn on the hands, the ability to easily keep the device clean was also highly valued. One user pointed out that if the product is intended to be worn all day, it places very high demands on not only comfort but also the ability to easily wash it.

Furthermore, the two users' opinions differed somewhat regarding the aesthetics of assistive devices. One user expressed little interest in aesthetics and valued function above all else. However, with the addition that if one had the opportunity to choose the color of the assistive device, it would be an appreciated factor. The other user expressed more thoughts about aesthetics, color, and form. In addition to an assistive device being small and lightweight, it was appreciated if it is not too eye-catching or has too typical medical attributes such as stainless steel or being beige or skin-colored, in an attempt to blend in, without much success.

Considering the experiences of stigmatization none of the two users interviewed felt particularly affected by it. When asked about it, one of the users did however admit applying great selectivity when choosing aids in terms of aesthetics and function, not wanting it to be too conspicuous, indicating that some consideration was given. The other user communicated not feeling affected at all but did at the same time point out that there probably is great variation in perceptions between people with spinal cord injuries.

Regarding independence, both emphasized that it is highly valued and desirable. It was also pointed out that the feeling of independence not only comes when the assistive device is in place but also during the putting on and taking off. If the user needs help putting on or taking off the assistive device, they lose a great feeling of independence. Components described as facilitating in the taking on and off are loops and zippers. Velcro straps have been common on assistive devices that the users have prior come into contact with, but these wear out easily and in addition attract dirt and were therefore not always appreciated.

The functionality of a grip assistive product, and in what way one would be supported in the gripping motion differed between the two potential users. The main reason for this was the difference in their existing hand function. One user had for instance no motor function in the little finger and was struggling overall with opening other fingers in order to gain a better and more comprehensive grip. This same user specifically expressed how much the device could facilitate everyday life if more fingers were included in the solution. Thereby, a need was not seen for a support in order to keep the index finger locked in flexion since the problem was rather in opening the finger and an open finger would allow for a greater grip. The same was not expressed by the other user who struggled more with managing to keep the index finger sufficiently bent in order for the thumb to end up in the middle of the lateral side of the finger.

During the interviews, the users also discussed their views on other aspects that contributed to a good grip, in addition to the actual strength and power of the grip. Sensitivity and friction were two central parts. Even if the users have reduced sensitivity in their hands, they learn how to work with it, and the feeling of an object against the skin can help grip better. Similarly, the friction between the skin and the object is important. One user increased friction by licking their fingers often and thus getting a stronger grip. They expressed how their grip was negatively affected, for instance, by cold weather or too much water, if, for example, they drove a wheelchair in the rain.

4.2.7 **Observations results**

As we did seek other forms of user observations than strictly physical, we turned to YouTube. We found one individual who was particularly interesting to use as a subject for observation. This individual, a north American female in her mid-40s with a C7 injury, had a YouTube channel dedicated to her life as a quadriplegic [36]. On this channel she regularly posted videos where we could follow her everyday life. Most videos were dedicated to a specific task such as baking or gardening where she showed the viewers how she performed these specific tasks. In these videos it was explained how this specific task was fitted for her abilities. It was well explained the differences between how certain procedures included external adaptation of the product/procedure as well as how the individual had learned how to adapt her abilities and routines to the situations.

In addition, we looked at an informative video explaining hand function after spinal cord injury [37]. This video explained both the anatomical aspects of spinal cord injury but also gave examples on medical tools that provided additional help for people with gripping problems. In this video, three individuals with tetraplegia demonstrated the use of their hands and the helping tools they use. This video highlighted the wide range of differences between different individuals regarding strength and ability although all the individuals with the same injury. The age span of the individuals in the video were between 18-45, where 1 was a female and 2 males. One of the individuals, with a C6 injury, emphasized that she did prefer to not use tools that adapt everyday subjects but rather preferred to figuring out a way on how to use them normally. She also highlights that each individual is different and that it's always good to try new things to find out if they work with your particular abilities. Another individual with a C5 injury and a tendon transfer surgery (where a tendon from a arm muscle that the individual can control is attached to a weak or paralyzed muscle in the forearm or hand), demonstrated the difference between strength and mobility in the hand that had undergone tendon transfer surgery compared to the one that had not. This part showed the big differences not only between individuals but also between arms on one individual. As well as how helpful the tenodesis grip may be. The last individual in the video demonstrated how he benefits from a wrist driven flexor hinge orthosis, (tenodesis splint) that enhances the tenodesis grip (partly in a similar way that the OneGrip does but without external force provided by a power supply). Overall, this video highlighted that hand function is unique to each individual which results in many different needs and wishes for the users of assisting gripping tools.

4.2.8 **Interviews with Tendo**

Interview 1: CEO of Tendo.

The CEO and founder of Tendo, Sofie Woge has dedicated her full time to the company and has great knowledge of the intended users, their wishes and needs. Over her years working with Tendo she has had the opportunity to meet several intended users and has seen many different prototypes that finally led to OneGrip. We have summarized the most important results from the interviews and divided them into three categories - the users - the functionality – and desirable improvements.

The users

- The user often has no to little sensations of feeling in the hands leading to an increased risk of abrasions and pressure sores as they do not feel if the material is sharp or adds excessive pressure on the skin.
- In her earlier works when focus was on rheumatic and stroke patients the aesthetic aspect was primary and a big factor in the users' choices of wearing or not wearing a medical device. For the current group of intended users this aspect is of interest but not as crucial.
- The users use this type of product to adapt themselves to the environment instead of adapting every aspect of the environment to themselves.
- The users use the tenodesis grip as a way of supporting their gripping motion and the product will work as an enhancement of that technique.

The functionality

- The product is designed in such a way that the user can put on and off the current product on their own. This thanks to the closely adapted details on the glove such as the loop in the Velcro strap.
- The intended users use different types of wheelchairs and in some cases they may want to use wheelchair gloves, these could then be fitted to be used over the product.

Improvement

- The current solution has potential to be made smaller and the company has a desire to reduce the size more.

- When the fabric of the glove becomes wet it dries slowly which may cause the user skin to get irritated or lead to abrasions.
- As the glove needs to be hand washed today the user needs an extra glove to use when the primary one is drying.

Interview 2: Glove designer at Tendo

The second interview was with Tendos product developer who has the head responsibility of the glove design. He described the challenges that come with developing a mechanically advanced product that aims to produce such a complex movement as the grip. We got a chance to see earlier prototypes of OneGrip and learn about the pros and cons with each prototype. We have summarized the most important results from the interviews in the following three categories - production-functionality – and material.

Production

- As the glove is a customized product that is manually sewed it provides difficulties when attaching the tendons to the fabric.
- No human hand looks like the other and that is no exception for the intended user group. In addition, the appearance and anatomy of the intended users can differ even more due to reconstructive surgeries and lack of movement in the muscles that result in muscle breakdown and structural changes of the hand. This is why so far, each glove is custom made.

Functionality

- There are critical points where the plastic tubes must be fixed for the gripping motion to become correct. One fixed point in the hand palm for the closing motion and one on the base of the thumb for the opening.
- The index finger must be closed and held in place for the gripping to be performed successfully and as an opponent for the closing thumb.
- The thumb needs to be positioned in correct opposition to provide an accurate grip.
- A friction material is necessary, on both the thumb and the closed index finger as friction in some cases has a greater contribution to a successful grip than force.
- It is important that the material is as close to the hand as possible with as little motion as possible, as motion in the fabric results in losses of pulling force.

Material

- The material needs to be wear and tear resistant as the glove is meant to be used in many different applications throughout the day.

4.3 Research conclusion

The main conclusions of this section can be summarized in the list below, followed by more in-depth reasoning:

- Great development opportunities were seen for the assistive aid, where it proved worthwhile to further investigate the possibilities for both soft robotic suits and exoskeletons.
- Within the target group there were wide variations in anatomy and functionality, resulting in different wishes for the aid and a likely need for individual adaption.
- There are potential and hopes of a wider area of use for a future product, e.g. involvement of more fingers and thus additional grips.
- For the current target group, function and comfort were prioritized over aesthetics and the people met in this project experienced little impact of stigmatization. One explanation could be the significant limited physical abilities and thereby limited options of aids, where users become more desperate for a solution increasing the highly sought-after physical independence.
- The emerging definition of independence present in every step of handling the aid, as well as the benefit of enabling the utilization of the existing sensitivity, were important aspects brought into the subsequent phases of the design process.

After collecting and analyzing all data, many opportunities as well as challenges could be seen for the development of this type of assistive aid. A well-developed product based on the users' needs and preferences could provide significant benefits for the users and contribute to a sense of independence.

Regarding the different types of gloves, soft robotics or exoskeletons, both had advantages that could be useful for Tendo's product. There were significant opportunities for both types, and a combination of these could also be advantageous. The essential aspect for the product was high comfort, great biomechanical alignment and that artificial tendons were allowed to move freely without significant losses due to friction or material movements.

In terms of this classification the glove currently developed by Tendo would count as a soft robotic suit. Just as the other similar solutions on the market today. The glove combines robotics, electronics, and wires with a glove of soft and flexible fabric. Important to point out is however that the general categorization into exoskeleton and exosuit is independent from the constituent materials of the device as well as its interface compliance. An external load-bearing frame does not necessarily mean a rigid or hard material for instance, and vice versa. This was an important aspect to bring to the idea generation, mainly in order to keep an open approach.

Looking at the user group, there is a wide variation in both anatomical abilities and limitations. Hands are highly complex, and there is a significant anatomical variation among different people's hands, such as sizes and lengths of fingers. This variation becomes more noticeable for this user group, where hands appear differently due to injury and various surgeries. The user's existing hand function also correlates to if, and what type of, assistive devices one might use. Additionally, it was essential that this type of assistive device would fit well on the hand and could be specially adapted based on how the hand looks, not only for the user's comfort but also for a good mechanical transfer of force from the motor to the finger through the artificial tendons. The product would therefore most likely need to include a solution for a personalized fit and possibly also custom features. They could for instance be about the thumb support that some users need in order to keep the thumb in a correct opposition position, or the support to keep the index finger fixed in a bent position.

When meeting with the users it emerged a present potential for the device to assist mobility for more fingers than the thumb, and thereby other kinds of grips in addition to the lateral pinch grip. The area of use may in the future thus be greater than that of the current product. Although the concept developed in this project was intended to fit the current engine and glove connector, and thereby mainly assist thumb movements, a solution with the index finger fixator as an optional add-on was justified to include depending on the user need, to provide the possibility of a more comprehensive grip for those who had the ability.

When looking at the users' desires and needs related to this type of device, there were also some variations. There was a clear difference in preferences compared to the responses Tendo previously collected when the user group looked somewhat different. For the current user group, comfort and the product's actual function were more highly valued than aesthetic aspects compared to what was communicated by the first user group. There was also a significant variation in the user group's product preferences, which can be linked to the various users' abilities and anatomical conditions. What one user wishes the product to perform may vary from another one's wishes, directly related to the individual's own existing gripping ability. It was highly important that the assistive device could perform in a way that was beneficial for the user, otherwise the user may choose not to wear it. What users had in common was their search for a way to increase their independence without sacrificing anything else.

There was also a difference between the previous and current target groups regarding the impact of stigmatization. In the earlier days of Tendo, stigma seemed to be a more prominent aspect to consider in the design process, which can be connected to the paragraph above regarding the importance of aesthetics. Thereto the expressed will of being able to hide one's aid and for it not to be a constant reminder to oneself and the surrounding. The focus was not as distinctly directed at stigma in the current target group of people with spinal cord injuries. A possible explanation for this may again relate to the physical abilities of the people within the two groups. Greater ability generally provides more options and with that space to take into account the appearance of aids as well as the point of view of the surroundings. People with further reduced physical ability are in more of a dependent position making those aspects play less of a role. This does, however, not mean that those aspects have no meaning for the current target group, as was also shown in some of the responses of the questionnaire and interviews.

We could see differences between the information gathered through interviews with the employees of the company and the information provided during the user interviews. The difference was mainly related to the highly valued aspect of independence, and what defines independence. The solution that exists at Tendo today is developed in such a way that the user most likely needs the help of an assistant to put on the glove, despite adjustments being made to the glove. This is a directly conflicting factor to what the users expressed, all steps of handling and using the product should be manageable for the user alone in order to provide greater freedom. Another aspect was sensitivity. In early studies done by the company's founders, the sensation of touch was an important factor when the user group looked different. With the current user group, this aspect has received less attention with the motivation that the users have reduced sensitivity. The opposite was evident in the interviews.

5 Define

In this chapter the user needs are defined. A template of need statements was developed, and then further categorized, processed and compiled into a function analysis chart to map out the functions the final solution should hold.

5.1 Identifying needs

The data gathered from the research was analyzed in order to better understand the needs of the users. Inspired by the first steps of the process by Ulrich and Eppinger for identifying customer needs [18, pp. 73-90], a data template was filled in where the raw data gathered from the research was interpreted into need statements. The template can be seen in Appendix A1. Based on the literature research, users' points of view, company requirements and context observations statements were formulated and listed in the first column of the template and then further translated into need statements in the second column. Each need statement was then given a specific number.

As could be seen, the template resulted in a relatively long list of need statements. Stepping into the subsequent development activities with such a large quantity of detailed stated needs may aggravate the work, implying a need for summarization before further use. Consequently, the next task was to organize and compile the needs into something easier to assimilate and work with. With influences from Preece, Rogers and Sharp [25, pp. 365-372] the data was analyzed qualitatively trying to identify recurring patterns and themes. Related need statements were thus initially organized into fitting categories, see table 5.1, and then further processed and compiled to some final defined needs presented in terms of a function analysis in table 5.3.

The function analysis thus introduces what functions the final concept is ought to hold, presented in each category as a verb + action. Further on they are assigned a classification based on the order of significance to the final solution, as Main function, Necessary function or Desired function. The abbreviation of the classes can be seen in table 5.2. Lastly it was stated which functions were relevant to the project's main prototype and which others instead were to be included in the final concept. This assignment can be seen under the "Type" column in table 5.3, with the categories prototype and concept.

Table 5.1 The need statements categorized.

Category	***Need no.***
Function	26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 39, 40, 41, 42, 43
Comfort	4, 5, 11, 14, 15, 16, 17, 18, 34
Material	5, 20, 21, 22, 23, 24, 38
Usability	7, 8, 9, 10, 11, 12, 13, 14, 15, 19, 22, 43
Design	1, 2, 3, 6, 11, 18, 25, 33, 39

Table 5.2 The classifications with associated abbreviations.

Class	***Abbreviation***
Main function	MF
Necessary	N
Desired	D

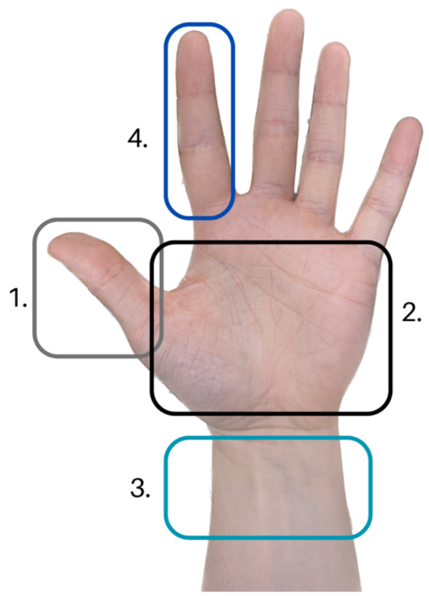
Table 5.3 The resulting function analysis.

Category	***Verb***	***Action***	***Class***	***Type***
Function	Support Enable	tenodesis grip · closing/opening of thumb · flexion/extension of wrist	MF	Concept
	Include	index finger fixed in flexion	N/D	Prototype
	Enable	thumb in middle of index lateral side	N	Prototype
	Keep	thumb in correct opposition	N	Prototype
	Include	fixed points for wires	N	Prototype
	Minimize	friction for wires	N	Concept

	Enable	friction in the grip	N	Concept
	Minimize	power losses	D	Concept
Comfort	Allow	adapted shape/alignment	N	Prototype
	Feeling	Airy	N	Prototype
	Advance	kindness to skin and joints	N	Concept
	Minimize	Weight	N	Concept
	Enable	aid comfort during whole day	N	Concept
Material	Advance	durability	D	Concept
	Suit	for contact with water/disinfectant	N	Prototype
Usability	Enhance	ease of cleaning	N	Prototype
	Enable	ease to maneuver	N	Prototype
	Enable	ease to take on/off	N	Prototype
	Enable	flexibility during other day activities	D	Concept
	Enable	portability	N	Prototype
	Advance	safety	N	Prototype
Design	Be	aesthetically pleasing	D	Concept
	Enhance	discreteness	D	Prototype
	Include	small/neat design	N	Prototype
	Minimize	wear and tear	D	Prototype
	Enable	free movement of intended joint	N	Concept

5.2 Defined focus areas

Based on the research of the current product, previous prototypes and the requirements defined above, critical areas or focus areas of the device could be defined. It was thus, these areas that were relevant in various ways for the glove that was to be developed, and that could be explored and experimented with in order to find the best solution meeting the defined needs. A concept image with the areas marked out can be seen in figure 5.1.



1. Thumb part with wires
2. Hand part with wires
3. Strap/Collection of cords
4. Index finger fixator

Figure 5.1 Defined focus areas of the glove to be developed.

The area numbered 1 refers to what in this project will be called the thumb part, and 2 refers to the hand part. The artificial tendons (wires) will in some way go along the thumb and hand (the palm and back of the hand down towards the thumb base) before continuing up to the glove connector. In these areas, or at least one of them, there is an additional need for the implementation of an abduction adjuster of the thumb, to keep it in the right opposition position. Below the wrist, area 3, it is mainly some form of strap that is needed to collect wires and cords so that these do not hang freely and become disturbing or risk getting entangled. Along the index finger, area 4, there are no tendons, that part is mainly to keep the index finger fixed in flexion. It additionally contributes to better grip of objects between the thumb and the lateral side of the finger if grip pads are attached. The parts of the glove that primarily affect the grasping movement itself as the main function are thus the thumb and hand part (area 1 and 2).

5.3 Conclusion

As the project aimed to generate a concept, where the fulfillment of needs was analyzed qualitatively rather than measured quantitatively, the product requirements were obtained utilizing a function analysis instead of listing quantified product specifications. The outcome of the function analysis could thus be seen as guidelines for the following product development. The objective of the function analysis was to communicate “what” is needed rather than “how” it should be implemented. Additionally, it can serve a purpose for several parties involved. The outcome provides the developers a guide on what to create as well as an aid to communicate that between each other. At the same time users and additional stakeholders can get an overview of what the solution may imply for them.

Moving forward in the process the objective is to produce a final concept where prototyping is used as a tool for evaluating different aspects, regarding the five stated categories: functionality, comfort, material, usability and design. Some of these prototypes intended for testing could include different parts of the final concept separately and not necessarily the entire system at once. The idea was then to supplement the final concept and concept images with a prototype providing a rough representation of what the final product may look like in physical appearance, thus not a functional prototype.

Based on the results from the user research the goal was to generate a concept that provided increased independence for the user in terms of physical function and use of the product, as well as suitable user interfaces to satisfy the usability requirements. All steps of handling and using the product should be manageable for the user alone in order to provide greater freedom. This to further establish a sense of increased empowerment and strengthened identity. There was an aspiration to achieve a product that would want to be used, feel good to use and become a natural part of what is worn on the body every day.

6 Develop

The development phase consisted of three different iterations. In the first iteration, numerous concepts were generated that could potentially match the users' needs and desires. In the second iteration, three different concept categories were further developed and tested. During this phase, significant advantages were observed in creating a glove using a rigid material, and this was therefore further evaluated and prototyped on in a third iteration.

6.1 General methods

The methods and approaches that were general for the entire development phase are described below. More detailed information about methods specific to certain iterations are described under the respective iteration sections.

6.1.1 **Prototyping**

To prototype means to test out and experiment with different variations, combinations, possibilities, i.e., different design options [26]. Prototypes include everything from sketches to simple models created with basic everyday materials available at home, to 3D-printed prototypes. The purpose of the prototype is to better understand the design problem, discover and develop innovative solutions and to explore and experience the interaction between the human and different designs [26]. For this project a combination of sketching, physical prototyping as well as computer models and 3D printed prototypes were used.

6.1.2 **CAD and Additive manufacturing**

Additive manufacturing refers to the process of creating a project by building it layer by layer. It can refer to any process where a product is built but it typically refers to 3D printing. In 3D printing one uses computer-aided-design (CAD) to produce geometric shapes by depositing material, layer upon layer with the help of a 3D printer. 3D printing is a suitable process for rapid prototyping as the manufacturing process is relatively fast and inexpensive [38]. There are different 3D printing methods and, in this project, we worked with FDM (Fused Deposition Modeling). In FDM printing the material is extruded through a heated nozzle to apply the material layer by layer until the part is completely built. This type of 3D-printing is suitable for basic proof-of-concept models and is quick and cost effective. In this project, we used a Prusa i3 printer and Polylactic acid (PLA) as printing material to produce simple concept prototypes with the aim of better visualizing the concept in user evaluations. PLA is a beginner friendly and easy to use material with a low cost. In the context of prototyping this material therefore is a suitable choice.

6.2 First iteration

The established problem definition, with subproblems and enclosed definitions of needs, formed a basis for the concept generation in the first iteration. Divergent thinking was approached with the effort of keeping an open mind. In this iteration different concepts were generated and sketched out. These were then discussed with Tendo, evaluated using an evaluation matrix and finally paired into general concept categories. Additionally, more detailed sketches were done for the specific thumb area.

6.2.1 **Methods**

Internal searching - Brainstorming & sketching

In order to keep a wide approach, inspiration was gathered from both external and internal research. External searching implies investigating already existing solutions, to the overall problem or to subproblems specifically. Implementing an already existing solution in a new context may lead to a faster process that is also economically beneficial [18, pp. 124-127]. The discovery phase was our external research, the literature study, market analysis, expert and user interviews as well as reviews of previous prototypes. Internal searching instead aims to utilize the knowledge and creativity of the developing team and its individuals [18, pp. 127-131]. This step of the concept generation is commonly the most open-ended during the entire design process. For the internal search several sessions of brainstorming were conducted together with sketching, individually as well as in groups. At the beginning of the development phase, the greatest focus was placed on the main construction, constituted by the thumb and hand area (area 1 and 2 in figure 5.1). The assisting parts of the glove such as straps and index finger holder (area 3 and 4 in figure 5.1 respectively) regained focus after the main construction and material properties of the glove were chosen. Sketching was used from early on and throughout the entire project to better communicate as well as understand the design of the glove and what possibilities and limitations that could come.

When the initial round of brainstorming and sketching sessions was finalized, the suggested solutions were explored in a more systematic way, in consultation with Tendo and through evaluation described in the section below. The purpose was to navigate through the ideas and possibilities by analyzing and, if possible, organizing them in a way that facilitated the work progress. A review of all ideas was made together with our supervisor at Tendo, to discuss the ideas and find out if any could be ruled out immediately, as well as if any were particularly interesting. Also, if Tendo had already tested some ideas that did not work and could be ruled out right away for that reason.

Concept evaluation - screening matrix

The concept selection signifies evaluating concepts with respect to the defined needs and additional criteria [18, p. 146]. Various methods can be used to compare solutions relative to their strengths and weaknesses. The purpose was to make a substantiated selection and scale down the number of solutions to those worthy of further investigation, prototype development and testing. At this early stage of the development phase, where the concepts are rough initially, it can be both difficult and misleading trying to make detailed quantitative comparisons. For that reason, concept screening was conducted as a fast method of approximate evaluation, offering a comparative rating system that is rough in its kind. The method utilized a screening matrix, providing space for rating and ranking of the solutions in order to facilitate the selection/elimination and make it more structured as well as objective. [18, pp. 151-156]

The current glove of Tendo's Onegrip was used as a reference concept, against which the generated ideas were rated relative to the defined needs and criteria. The rating codes were "better than" (+), "same as" (0) or "worse than" (-), thus corresponding to how each solution rates in comparison to the reference. The rating of the reference was thereby set to 0 for each selection criteria. Seven selection criteria were included: Airiness, Size, Force transmission, Grip friction, Durability, Weight and Ease of cleaning. When all solutions were rated the scores were summed up. Based on the summation the solutions could be rank-ordered and evaluated for further development.

6.2.2 **Results**

An overview of the initial sketches can be seen in figure 6.1, and more detailed descriptions of each idea are presented in Appendix B1.

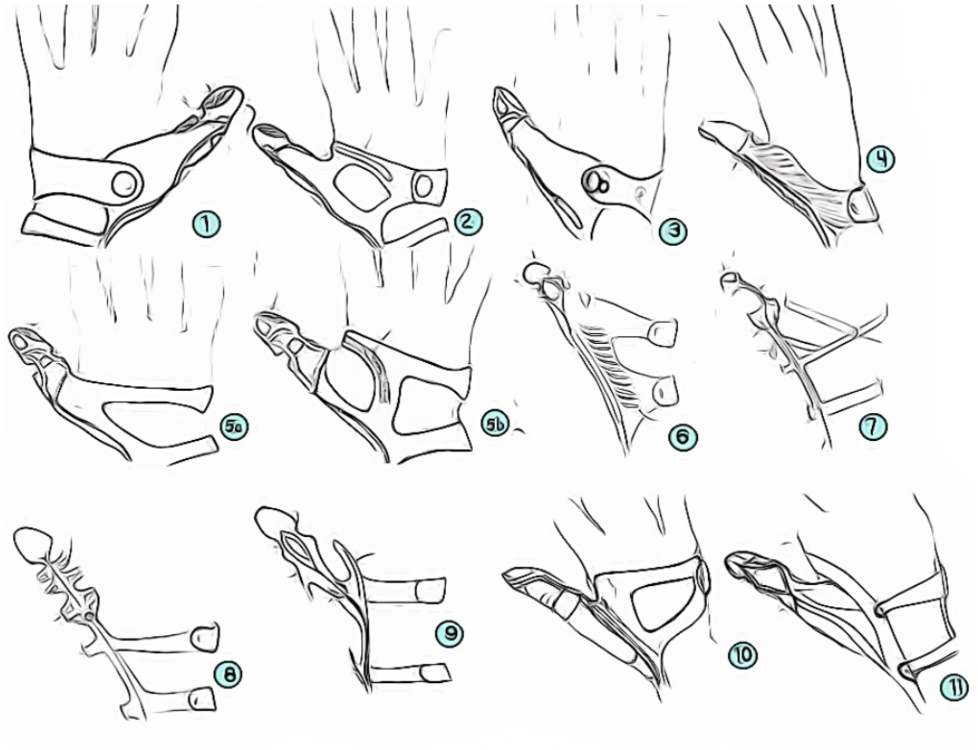


Figure 6.1 Collage of concept sketches

During the meeting with our supervisor at Tendo, all sketches were reviewed generating a discussion about the overall concepts as well as somewhat more detailed options of solutions. No concept was ruled out immediately; instead, the benefits of testing concepts or ideas through simple prototypes, in order to see how they really will behave was highlighted. Some challenging aspects in this type of product, which the company itself has struggled with, were discussed. This included the movement of fabric, slipperiness of hard materials and friction between artificial tendons and other parts of the glove.

6.2.2.1 Concept Categories

When going through the sketches, it was relatively simple to see common denominators in several solutions. Pairing those which had certain similarities into a category resulted in three general concepts presented below.

Soft Exosuit

The first concept category was based on a soft, non-fabric-based material. A material that still has the positive aspects of what Tendo has achieved so far with its fabric-based glove, such as light weight, flexibility, gentle on the skin, comfortable to wear all day, but which at the same time allows for better cleaning of the glove.

A glove in a silicone-based material or in TPU (thermoplastic polyurethane) would enable the user to more easily expose the glove to wetness in their everyday activities and the material would also allow for a quicker and easier cleaning of the glove. A glove made in a soft material, may be compliant along the skin, but must at the same time be stiffer around the areas where the wires attach so that the wire trajectories are not compromised. Inspiration came from training gloves, wheelchair gloves, as well as from the material of activity watch bracelets, which many people use in everyday life and are durable, comfortable, and easy to clean.

Rigid Exoskeleton

The second concept category was a more rigid link-based exoskeleton, a network of parts linked and moving in relation to each other resulting in a non-full coverage glove. The concept was based on the possibility to integrate channels in the rigid parts for where artificial tendons could run. Plastic based rigid parts could easily be wiped off and cleaned. Rigid parts custom made to a close fit for the user, with for example measurement generated from a 3D scan of the hand, have the potential to result in a comfortable and well-fitting product, something highly requested from the users. The rigid parts could potentially be a solution to the problem experienced by the company regarding fixed points for the artificial tendons. Certain fixed parts, where the pulling force in the tendon does not result in any motion in the surrounding and anchoring material, are necessary for a successful force transmission as well as correct gripping motion.

Combined

The third concept category was a combination of rigid and soft parts, for instance suggesting a rigid link-based thumb part combined with a soft part over the rest of the hand or a mixture of rigid and soft links in one or both parts. For instance, all fixed anchoring points in the thumb, palm and base of the thumb could be supported by a rigid material and then be covered in a softer compliant material forming the main glove. This combined concept could have the benefit of more efficient force transmission through to the rigid parts, and at the same time provide great comfort and compliance thanks to the softer materials.

6.2.2.2 Concept screening matrix

The screening matrix, including the resulting ratings, can be seen in 6.2. Concept 1-4 as well as concept 6 obtained the lowest net scores, indicating comparatively small improvements overall from the current OneGrip solution, and were thereby excluded from further development in this project. For the remaining concept ideas, the higher scores suggested great potential in creating solutions that entailed improvements well connected to the defined needs. These were therefore kept in mind in the continued work of the development process.

	Concept												
Selection Criteria	**Tendo**	**1**	**2**	**3**	**4**	**5a**	**5b**	**6**	**7**	**8**	**9**	**10**	**11**
Airiness	0	-	-	-	0	+	0	0	+	+	+	+	+
Size	0	0	0	0	+	+	0	0	+	+	+	0	+
Force transmission	0	-	0	+	-	+	+	-	+	+	+	+	0
Grip friction	0	+	+	0	+	0	0	+	0	0	0	0	0
Durability	0	+	+	+	+	+	+	+	+	+	+	+	+
Weight	0	-	-	-	-	0	0	0	+	+	+	+	0
Ease of cleaning	0	+	+	+	+	+	+	+	+	+	+	+	+
Sum +'s	0	3	3	3	4	5	3	3	6	6	6	5	4
Sum 0's	7	1	2	2	1	2	4	3	1	1	1	2	3
Sum -'s	0	3	2	2	2	0	0	1	0	0	0	0	0
Net score	0	0	1	1	2	5	3	2	6	6	6	5	4
Rank	-	7	6	6	5	2	4	5	1	1	1	2	3
Continue?	-	No	No	No	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes

Figure 6.2 Screening matrix with resulting scores.

6.2.2.3 Thumb area

Additional detailed sketches for the complex thumb were created, these can be seen in figure 6.3. These were created as a result of vague and undetailed thumbs in the concept sketches.

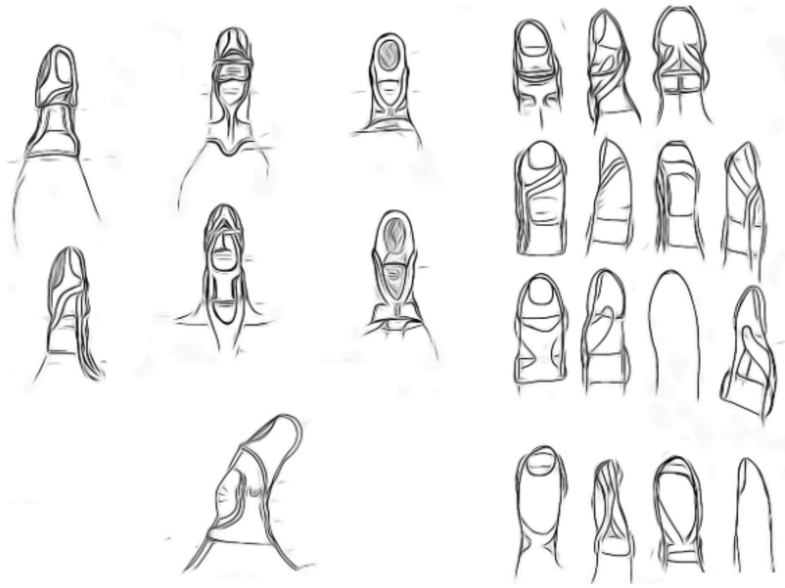


Figure 6.3 Sketches of thumb concepts.

Most of the newly generated concepts for the thumb were based on various constructions of rigid linkages, mainly because of the advantages they offer in terms of possibility to airy constructions and built-in fixed anchoring points. As mentioned earlier there could be benefits from a mechanical perspective if the links had the right alignment and fit. Inspiration for the design of the thumb parts were drawn from previous prototypes shown by the company, thumb prosthesis and orthoses.

6.2.3 **Conclusion**

The main conclusions of this section can be summarized in the list below, followed by more in depth reasoning:

- The main reasons for lower grades in the evaluation matrix were the size and airiness of the solutions, along with potential issues such as unwieldiness, heaviness, sweatiness, and material movement.
- Comfort and ease of handling were important considerations that needed greater attention in later stages as they were hard to evaluate in this early phase.
- Based on the results of the screening matrix, the focus of further development would be on either rigid linkages or a combination of soft and rigid components.
- Further investigation was needed on how to design the thumb and route the wires within it.

Analyzing the evaluation matrix result, one of the main reasons causing lower grades was the size and airiness aspects of the solutions. The concepts that received lower rankings covered as much of the hand as OneGrip, and with a material such as silicone it could probably become both unwieldy, heavy and sweaty. Having a soft and compliant material over both the hand and thumb, with little to no rigid support, would probably also entail the same negative impact on the force transmission as the current product. For a solution in a softer material that only went to the bottom part of the distal phalanx of the thumb, as in concept 4, figure 6.1, a problem was also seen with keeping the construction in place without it falling off.

In addition to the selection criteria included in the screening matrix, two other important aspects discussed in relation to the defined needs were Comfort and Ease of handling. However, in such an early stage of the development process these were found hard to evaluate. The goal was to succeed in creating a product that should fulfill both these criteria, to be comfortable and easy to handle, regardless of the concept that was to be developed. In other words, the potential to succeed was seen in all suggested solutions. In addition, at this early stage of idea generation, most in-depth details were excluded. Details that otherwise could have included solutions for specific handles or loops facilitating maneuvering. The defined needs that were not included in the screening matrix were thus not less relevant for the final solution but received greater attention in the later stages of the process.

The outcome of the screening matrix implied that further development would focus on rigid linkages or a combined concept of soft and rigid parts. These two concepts both had advantages and challenges making further investigation needed to examine how combinations of constructions and materials would perform in a robotic glove. Most of the remaining generated ideas had separated parts for the thumb and hand, each part with their own challenges regarding design, comfort, placement of wires plastic tubes etc. To facilitate the further process, the thumb part and the hand part (area 1 and 2 in figure 5.1 respectively) were worked on and developed separately. This to be connected and form one unit again, together with the additional assisting parts, at a later stage of the process.

A challenge with the design of the thumb would be to further investigate how to build in the wires in the construction, so that they did not lie freely and rub against the skin or were unprotected in large parts, but still generated pulling with the optimal force and direction. An optimal routing of these wires required extensive research and mechanical calculations. While this aspect fell outside the scope of our project, we still wanted to explore it in the further development process using simple means to get an indication of how the result might turn out with different routes. In addition, it was important to ensure free hinging movement of the joints by avoiding material or wires getting in the way and counteracting the movement or being pinched.

6.3 Second iteration

During this iteration, we wanted to explore the potentials and challenges with our generated concepts by taking a closer look at how different materials behave in this type of glove. We wanted to see if we could gather any insights about the comfort and feel of the different concepts by testing and prototyping with various materials. Based on the resulting concept suggestions and screening matrix from the first iteration, soft as well as rigid solutions were created, tested and evaluated for the hand part whereas the thumb part was further investigated and prototyped with rigid links. The focus was to examine certain material properties and thus not too detailed focus was put on what the exact materials of each concept would be.

6.3.1 **Methods**

6.3.1.1 Prototypes

Soft hand prototypes

For the soft based concept, a flexible PVC (Polivinyl Chloride, without addition of phthalates) was initially used as prototyping material. It is a thermoplastic material, durable with silicone or rubber-like properties and moreover water resistant [39]. This material was used for fast prototyping in order to test out different sizes and shapes of the glove. The idea was to examine the possibilities of creating compliant prototypes that offered a relatively airy design, with high comfort and body alignment, without being too cumbersome on the hand. Before using the PVC various designs were created using tape on the hand. These creations further constituted templates for when the shapes were to be cut out of the thermoplastic material.

Another prototype for the soft concept was made with two-component silicone rubber. The silicone rubber was mixed and then placed directly on the hand for molding and hardening. The idea of a molded glove enables for a close fit to the user's hand and hence better mimicking the hand's natural biomechanics when the artificial tendons are pulled. The two-component silicone rubber was chosen to test flexibility in the glove but at the same time evaluate its resistance to movement in the material when the artificial tendons are moved, i.e., force losses due to material movement. In this prototype the plastic tubes were glued to the prototype and additionally secured with duct tape. For the strap a piece of the PVC material was cut out and mounted to the molded part with the help of a clip-on buttons.

Rigid hand prototypes

The first rigid concept prototype was made from polymer clay. The clay was formed directly on the hand and plastic tubes were molded into the clay before letting the clay harden in an oven. Rubber bands were used as links between the two separate rigid parts to keep them in place.

An additional simple 3D prototype was made as a proof of concept to test printing channels for the plastic tubes. A 3D sketch was constructed in CAD and then printed in an SLA printer. The parts were connected with a piece of the PVC material.

Thumb prototype

The sketched ideas from the initial concept generation of the thumb were explored further. Low-fi prototyping was performed in order to get an idea of what the concepts might look like. In order to examine the right placement of wires a session was held where different placements of the wires were tested. The tubes, with wires passing through, were attached onto various sites on the thumb with duct tape and then pulled. The intended thumb part was furtherly designed in CAD and then printed in a FDM printer as a proof-of-concept to test the suitability of a rigid material for this kind of design, apart from testing the design itself. Grooves were made to simulate the wire guiding plastic tube tunnels, as it was not possible to print such small tunnels in a FDM printer. In order to test the prototype as intended with friction material, fixing pads in self-adhesive silicone was attached over the finger pad surface thought to be most involved in the grip.

6.3.1.2 Tests and evaluation

Hand Part

An evaluation of hand part prototypes was made containing two different focus areas. The first part of the evaluation aimed to examine the mechanical behavior of each prototype, primarily to see how the different materials behaved when artificial tendons were mounted and pulled. The prototypes were then examined to get an indication of what the comfort and interaction between device and skin felt like.

The prototypes were put on the hand ensuring right placement of the plastic tubes. A thin steel wire was then pulled through the plastic tubes and taped to the prototypes and pulled manually in order to simulate the pulling function of the products engine. Each prototype was kept on for a couple of extra minutes in order to get an idea of the comfort after somewhat longer use. The questions aimed to be answered with the tests were the following:

- How does the material behave when the tendons are pulled?
- How does the material feel against the skin?
- Will a solution in this material be comfortable?

Thumb Part

An evaluating test was performed on the thumb prototype, aiming to examine attributes such as fit and comfort, but also functionality aspects such as placement of wires and free movement of joints for full flexion and extension. As a main function of the intended solution, the grip of objects had to be examined. Thereby, another focus area of the test was to evaluate the suitability of the hard material as well as the construction for gripping objects of various shapes, sizes and with surfaces of different hardness.

The construction was put on and kept on for a while to examine more long-term effects regarding skin-device interaction. The fit and alignment were observed, and the joint mobility was tested manually without wires. For evaluation of the grip, grasping of a pen, a book and additionally a sock was performed utilizing a lateral pinch grip assisted by the tenodesis function. The questions aimed to be answered with the test were the following:

- How does the construction fit and align with the body?
- Is it a comfortable solution?
- Does the design allow free hinging movement of the MCP and DIP joints?
- Is the placement of wires suitable or are they at risk of getting in the way or being pinched themselves?
- Is the construction suitable for the grip of objects?
- Are the material properties suitable for the grip of objects?

6.3.2 **Results**

Soft hand part prototypes

The resulting soft prototypes are shown in figure 6.4 and 6.5 below. Three of the prototypes in figure 6.4 had a part that went up around the proximal phalanx of the thumb. This part was not meant to be in the same soft material but rather presented to illustrate a rigid thumb part that the softer material attached to. This in order to investigate how the hand part could attach to the thumb and still leave space for hinge movements of the MCP joint. None of the prototypes in this same figure have tubes attached but were all designed with space for the tubes to go along the inside of the hand as well as the dorsal thumb and thumb base, just like in the OneGrip solution. The tubes were later sewn and glued onto the material with an instant superglue and additionally secured with duct tape in order to test the intended functionality of the design and material. The arrangement can be seen on one of the prototypes in figure 6.5.

Figure 6.4 Soft PVC prototypes.

Figure 6.5 PVC prototype with plastic tubes and wire (left) and prototype in two component silicone (right).

Rigid hand part prototypes

The clay prototypes and the 3D printed prototypes can be seen in figure 6.6 and 6.7. The rigid hand prototypes consisted of two separate smaller parts that were connected together with an elastic material. For the clay prototype a rubber band was used and for the 3D-printed one a piece of the PVC material.

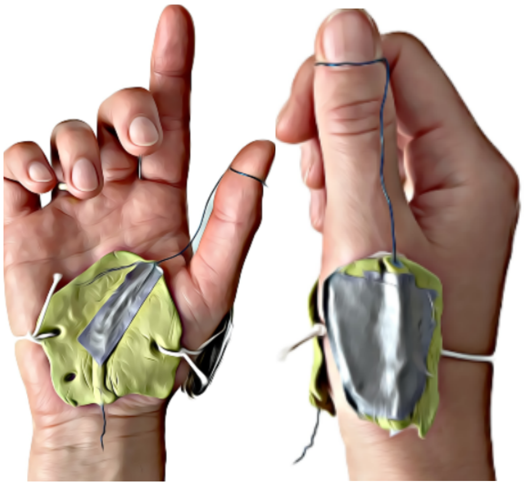


Figure 6.6 Prototypes made out of clay.

Figure 6.7 Simple 3D printed parts.

Thumb part prototype

The created thumb prototype can be seen in figure 6.8. The emerging idea was to include two rigid parts linked together with a hinge-like solution and leave as much space as possible for the joint movements with no material in the way. The connection of the parts was thus placed out on the lateral sides of the thumb. The area over the finger pad was additionally left free from tubes or any details that could get in the way of the grip surface.

Figure 6.8 First 3D printed thumb prototypes.

The consequent result from testing various placement of wires can be seen in figure 6.9. The wire pulled in for flexion (red in figure) loops around the distal phalanx and gathers down on the palmar side to proceed along the inside of the hand. This generated a pressure more directly on the thumb, compared to if the wire had only gone on top of the thumb or on the palmar side and pulled primarily on the material. Since wires over the grip surface wanted to be avoided the wire pulled for extension (blue in figure) had to go in a loop remaining on the dorsal thumb all along, with attachment at the lower distal phalanx.

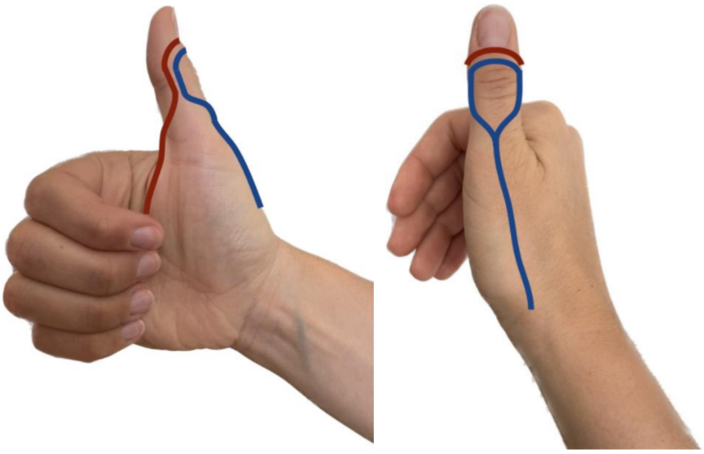


Figure 6.9 Illustration of artificial tendon placements.

Hand prototypes evaluation

What could be clearly seen with the softer prototypes was that the material moved when the tendons were pulled, contributing to force losses, even though the glove was almost molded to the hand. There was less movement in the prototype that was made from two-component rubber, which was also much better shaped to the hand.

In a short term use the soft parts were compliant and comfortable against the skin. It was however clear that a silicone-like material being cut out flat, as the PVC, does not align as well with the body. The generated designs did not follow the hand curvature completely, causing the outer edges to stick out from the hand and bulge slightly with movement. With such a material some kind of harder malleable support structure would be needed.

The soft parts were also very warm, especially the two-component part that was close to the skin when worn for a longer period of time. Even the attempts to make airier PVC designs with more open surfaces, as the prototypes second and last from the top in figure 6.4, became too sweaty against the skin after some time.

What became clear with the 3D-printed parts and the clay parts was how easy it was to hold the tendons in place in the right position as they were tightly embedded in the material and did not move when pulled. The material did moreover offer a rigid protection of the wires, with no need for additional tubes in those parts, and the wires could move effortlessly without friction. The 3D printed prototype had, however, too thin walls on the channels for the plastic tube and easily broke.

The clay part positioned on the outside of the hand had a very poor fit, even though it was shaped after the hand. The part melted in the oven during curing and lost its shape, which made it difficult to feel the full potential regarding comfort of the solution as a whole when moving the thumb. However, the palm part had a good fit and the material felt smooth and comfortable against the skin.

Thumb prototype evaluation

The thumb prototype showed promising results of having a solid thumb part that enabled a good bending moment. Thereto it offered great space for free movement in the DIP joint with no additional material interfering. The wires could be well hidden with built-in anchoring points. It was only in the small area of crossing over the two rigid parts in the current design, thus the parts that went over the proximal and distal phalanges respectively, that they had to run freely. This since bending of the tubes would cause the wire to pinch. Since it was such a short distance with open wires and the area was placed out on the lateral sides of the thumb, there was little probability of something going against the wires preventing their movement.

Due to slightly too big sizing, the proximal phalangeal part of the thumb construction ended up a little bit in the way, counteracting the flexion movement in the MCP joint. An appropriate size was needed in order to determine if the problem persisted. The distal phalangeal part of the design did additionally not align that well with the shape of the body, not following the curvature of the fingertip, causing it to be somewhat loose and cumbersome. Thereto, this part became somewhat confined leaving wishes for a slightly airier solution.

The rigid based design worked well for gripping the selected objects. Unless the friction material over the grip surface was included when gripping harder objects such as the pen and book, the interaction would tend to become somewhat slippery due to the rigid surfaces from both sides not offering any compliance. It was then additionally harder to grip the pen with its round shape, compared to the flatter book. However, with friction material attached at the grip surface, as intended all along, both objects could be grasped without much effort. In addition to friction this material offered a more flexible and malleable surface, more adaptable to the object surface. The compliance was not perceived as much of a problem for the grip of the sock where the object itself was more pliable. However, even for the thin sock fabric that could be somewhat slippery in itself (especially with impaired grip strength), friction material facilitated the gripping significantly.

6.3.3 **Conclusion**

The main conclusions of this section can be summarized in the list below, followed by more in depth reasoning:

- The soft prototypes showed shortcomings in terms of heat, sweating, and fit.
- The advantages of the rigid parts were numerous, especially in terms of a good fit, power transmission, and the ability to design a neater construction.
- The rigid parts were selected for further development, and more focus was needed on the refinement of a complete concept.
- A rigid thumb allows for customization of parts according to individual needs and indicates stable power transmission to the grip.
- Friction material is needed to achieve a good grip, especially with the rigid parts.

Heat and sweat are something that causes discomfort in general and have a negative impact in terms of friction towards the skin that may also lead to increased risk of abrasions, something the user group already has an increased propensity for due to impaired sensitivity. The soft glove concept had not only limitations in proper fitting to the hand, but it was very warm and additional sweating was caused due to the compact material. Even without sweat and heat, the material itself caused friction against the skin that could additionally result in difficulties when putting on the glove. This aspect could result in a direct negative impact on the so highly asked for, increased independence from the users as they might need assistance to get it on. Additionally, the soft glove concept had limitations regarding the material movement following pulling force in the tendon. The mainly positive aspect was the ability to easily keep the glove clean and wipe it off with water or disinfectant. Thereto they provided built-in friction for the grasp.

The rigid based glove concept showed more promising results regarding force transmission and potentials in proper fitting to the hand in the testing. A big advantage of a rigid structure in terms of making it more compact, occupying a smaller portion of the hand, was the material's ability to support itself. A rigid material does not require the same extent of attachment points as a soft material. The hard material additionally allows for easy cleaning and washing, and it dries quickly. Including soft components in a solution would still require a rigid framework for more efficient power transmission. To focus on developing a rigid construction exclusively was thus considered appropriate, offering a simpler and neater solution. If the beneficial grip friction of the softer material would be desired, potential was moreover seen in coating specific outer parts of the construction with a friction material.

These results together with the results from the evaluation of the first iteration contributed to the choosing of the rigid concept for further development. Furthermore, the company found the idea of a glove made of a rigid material intriguing. They had contemplated it themselves but hadn't had the opportunity to explore it further. This served as additional motivation to proceed with the rigid material, as it aligned with their vision and offered potential benefits in terms of usability and stability for the users.

More focus was needed on the shape and alignment of the rigid concepts to better achieve and test comfort. The rigid material assisted to keep the plastic tubes and tendons in place, but a solution to secure the placement of the rigid parts on the hand needed further development. Additionally, further work was needed for a connection with the thumb. This involved developing a mechanism or interface that allows seamless integration and coordination between the hand and the thumb, ensuring optimal functionality and comfort.

The rigid based thumb concept demonstrated significant potential for utilizing a rigid structure for the thumb. It allowed for customization of the different parts to accommodate various thumb sizes. Moreover, using a rigid material indicated good force distribution throughout the structure, enhancing overall grip strength and control. The further work would aspire to more closely mimic the shape of the thumb. There was room for improvement regarding the conformation and fit, mainly for the distal phalangeal part of the construction which would need to taper more and be rounder in shape. Continued focus would also be put on making the thumb section more breathable and lightweight, enhancing user comfort.

The construction and rigid material were considered well-functioning for the grip of objects, which strengthened the motivation to continue developing this concept for the thumb. The importance of a softer friction material over the grip surface however clearly emerged during testing, providing significantly better grip for all shapes and characteristics of surfaces. The material provided better friction than the skin itself and compensates for weaker grip strength. A certain thickness of it would thereto be beneficial in order to obtain an extent of softness and thereby compliance as well as malleability along the interacting surface with the gripped object. The grip could feasibly also be improved through better body alignment and a shape more similar to a real thumb.

6.4 Third iteration

In the third iteration the aim was to further develop the concept of rigid links for both thumb and hand. This concept showed promising results in the first prototyping and material evaluation tests. In further development a solution had to be found for how the rigid hand parts, along the inside of the hand and outer thumb base, could be anchored to be able to stay in place. Additionally, the concept was developed in its entirety, with a strap and a solution to keep the index finger bent.

6.4.1 **Methods**

Brainstorming and low-fi prototyping

New rigid based concept sketches and additional freehand prototypes with duct tape and PVC were made in a new brainstorming session. Out of this a new CAD construction of the hand part was developed and then 3D printed in a FDM printer. The CAD construction of the thumb developed in the second iteration was additionally further developed, based on the outcome of the evaluation, and a new thumb part was 3D printed. With more concrete proposals for the designs of these main parts, an overall concept was established with all the parts that were intended to be included in the final solution. This was first presented graphically and then prototyped, with existing and additional parts. This was done with the aim to get a feeling of the actual physical representation of the concept on the hand and use as visualization in user evaluations.

Interviews and concept evaluation

In rehabilitation engineering the focus is on the user and their needs and preferences. Feedback from potential users early in the development process has a big impact on how successful the outcome of the project may be. The concept was therefore presented to two intended users, the same individuals that prior had been interviewed, in semi structured interviews with the aim of evaluating the design. One meeting was an online video meeting and the other was in person in the user's home. Firstly, the sketches on the suggested concept as a whole were shown and described and later on, the prototype was shown. In the meeting conducted in person the user also had the chance to feel and try on the prototype. The prototype was non-functioning in the means of providing a gripping motion and the functionality was therefore not evaluated.

The idea was to direct the conversation into some prepared questions to be answered, but then leave room for the user to speculate and develop their answers, add comments and express any spontaneous thought that may arise. Some of the prepared questions aimed to be answered by the user during the meeting were:

- What are your spontaneous thoughts about this concept?
- What do you think about the:
    - Shape?
    - Color?
    - Material?
- Is there anything about this concept that stands out? Positive or negative?
- Is there anything you see as a potential problem/difficulty?
- Would you be willing to try and wear this aid?
- How do you view the ability to put the aid on and off?
- What are your thoughts and opinions on the buckle?

6.4.2 **Results**

The idea was to merge the two hand parts together into one rigid piece and keep it in place by anchoring it to the thumb part as well as a part going around the index finger, keeping it flexed, see figure 6.10 and 6.11. To avoid the glove covering a large area of the hand, a variant was tested that only included one strap below the wrist, intended to be able to hide inside a long-sleeved shirt. However, an insight was that it would be beneficial if the hand part could stand on its own, so that the MCP joint could be free of material dorsally and so that the construction was not dependent on the part of the index finger, as not all users would need it. This led up to an idea of making the rigid hand part going around the thumb, implying no need for the previous anchoring points. The proposal was further investigated and developed resulting in a one-piece rigid frame printed in the FDM-printer, seen in figure 6.12. An additional print was made, with the same design but with grooves in order to attach plastic tubes, as wire passages on both sides of the hand, which can be seen later on in figure 6.15.

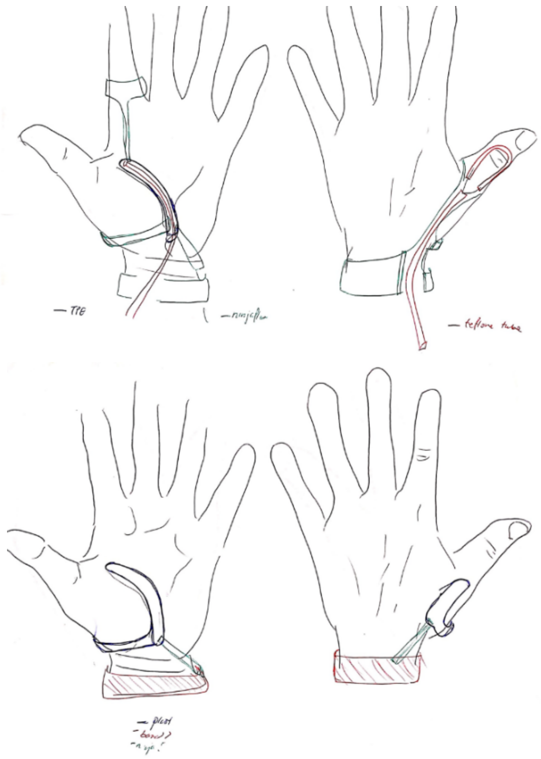


Figure 6.10 Sketches of a new rigid concept.

Figure 6.11 Freehand prototypes made out of duct tape and PVC.

Figure 6.12 The resulting rigid hand part going around the thumb.

New thumb prototype

The prototype resulting from the adjustments in the new iteration of the thumb can be seen in figure 6.13. An opening in the distal phalangeal part of the construction was added in order to make it airier, placed over the thumb nail between the two wire passages. The upper wire that pulls the thumb into flexion was thereby moved a little bit higher, however still looping around the dorsal side of the thumb generating a direct pressure. The construction was further trimmed, in terms of a smaller size and more tapered shape in order to better align with the fingertip. The tubes that form passages for wires were attached to the outside of the structure along printed grooves.

Figure 6.13 Second 3D printed thumb prototype.

The concept in its entirety

At this stage in the process, a preliminary overall concept was established based on the developed parts so far and adding on the remaining parts to prototype. Now that there were well-defined proposals of what the hand and thumb parts could look like it was an appropriate time to start implementing the additional index finger fixator as well as strap and buckle.

The resulting overall concept, seen in figure 6.14 below, was based upon close-to-figure rigid parts with integrated plastic tubes for guidance of the artificial tendons. The idea of the small rigid part was to take up a smaller part of the user's hand as well as move the anchoring point higher up on the underarm for a more discreet appearance. The rigid hand part ran around the thumb base and was connected to a silicone-based wrist band with sidelong elastic bands to help keep it in position. These elastic bands also kept the plastic tubes in place during movement in the wrist. The plastic tubes were intended to be collected in a shrinking tube that led them up to the control unit. The wristband consisted of a loose loop, that could facilitate when taking on the glove, with an additional magnetic buckle. The buckle had a loop for the user to easily close and open the buckle as well as tighten the wristband. The thumb part had an opening for the thumbnail to offer an airier design as well as more resemble the thumb. An optional strap was available for locking the index finger in a bent position. Grip pads were placed on the thumb and on the index finger strap for extra friction.

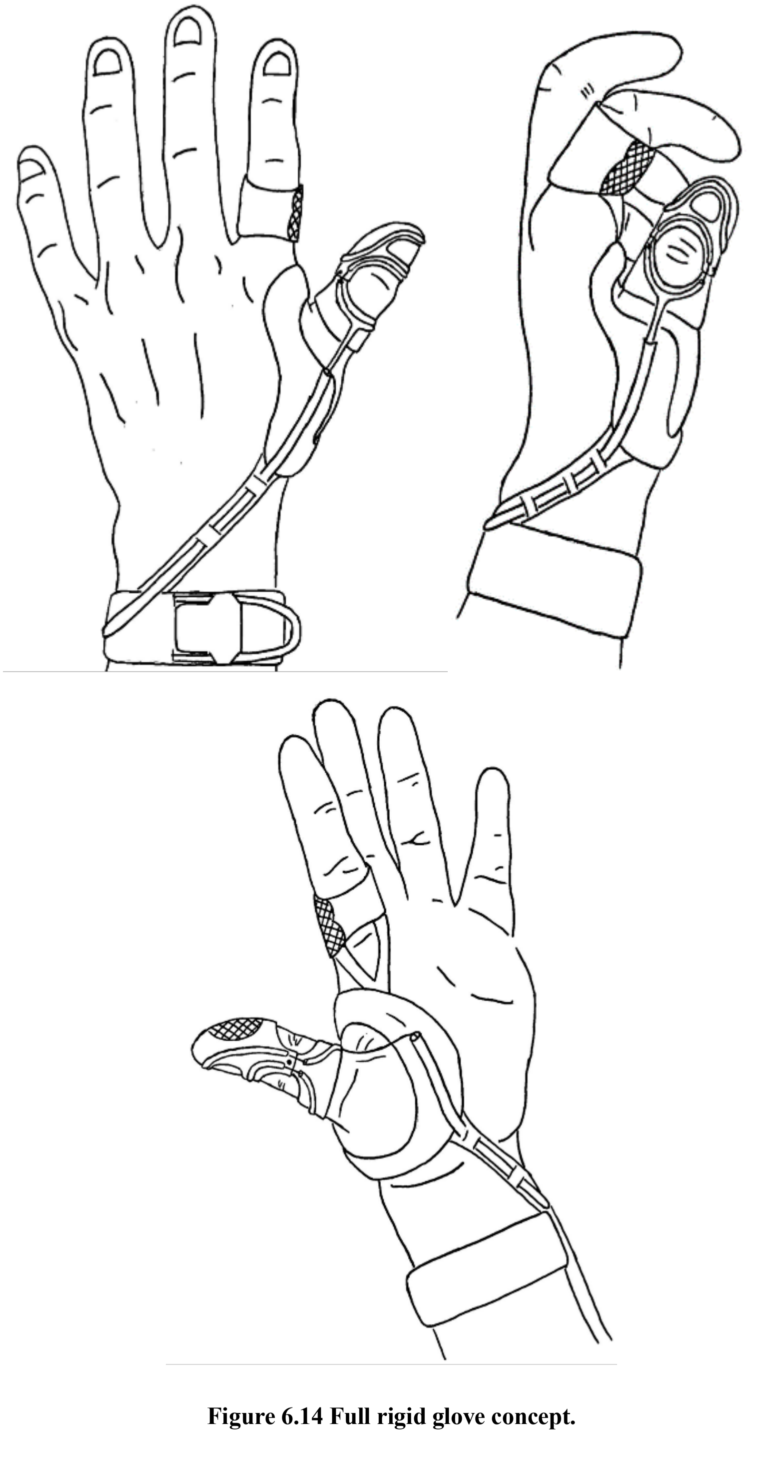


Figure 6.14 Full rigid glove concept.

Concept prototype

In the prototype created to visualize the proposed concept, seen in figure 6.15, the rigid hand part of the glove was intended to follow the hand's natural curvature with a good fit. The part had grooves where bigger plastic tubes were glued in place. The thumb part consists of two separate parts that linked together in a way that enabled hinging motion for the joint. These parts as well had grooves where smaller plastic tubes were glued in place. Fishing line was used to simulate the artificial tendons and thread through the smaller tubes. The solid hand part connected to a wrist band, cut out from PVC material, with elastic bands. The small tubes were thread through the elastic band to keep them in place. A magnetic lock was placed on the wristband, with an implemented loop to facilitate handling. The index finger holder was constructed by attaching a piece of fabric on the inside of the palm using glue. A push button was placed over the fabric. At the other end of the fabric, the counterpart of the button was attached, allowing this part to be closed. Another image of the prototype can be found in figure 6.16, showing how all parts of the device positioned below the wrist easily can be hidden with a shirt sleeve.

Figure 6.15 Prototype of full rigid concept.

Figure 6.16 The concept prototype when user wears long sleeve.

Concept evaluation

Overall, both users were positive about the design of the glove and its minimalistic appearance, they were genuinely surprised at how small it was. In the remote meeting the user was intrigued by the small appearance of the glove and appreciated that such a little part of the hand was covered.

The fact that the index finger was not completely covered and that mainly the proximal phalanx was locked in position was appreciated. Both users had previously been in contact with OneGrip with its full enclosure of the index finger. None of the users saw any benefit in having the entire finger covered and locked. They pointed out the importance of having friction material at the bottom part of the index finger when kept in flexion, but beyond that argued that material over the entire finger is unnecessary and only creates heat and discomfort. They also inquired whether it's intended to be possible to replace the friction material since both have noticed that this type of material wears out very quickly.

The magnetic clasp was positively received by both users as they yet again highlighted the issues with Velcro straps, which wear out and easily collect dirt. They appreciated the loops on the clasp and wished that the part that is tightened and secured does not hang loosely, but also attaches so that nothing risks getting caught in the wheelchair wheels.

The one user that had the opportunity to try on the glove managed to do so independently, by positioning the glove on the lap, threading the hand through the wristband and then the thumb through the hole of the "glove". The thumb was inserted into the thumb parts and then pressed into place with the help of the other hand. The wrist band was hard to tighten as the material being pulled together was too bulky and therefore it could not be properly closed.

Another feedback point given by the user who tried the prototype was the positioning of the plastic tubes. The tubes ran along the elastic bands and met on the outer side of the arm to line up and connect to the electronics and motor unit on the upper arm. This particular user would prefer it if the tubes were placed on the opposite side of the arm as the outer side of the arm is used when braking the wheelchair.

6.4.3 **Conclusion**

The main conclusions of this section can be summarized in the list below, followed by more in depth reasoning:

- A complete concept for the glove was created, resulting in a compact design intended to be produced based on a 3D-scan of the user's hand.
- Limitations with FDM printing resulted in the prototype not fully resembling the intended concept.
- The thumb part showed promising results however, there was still room for improvement to further mimic a real thumb.
- The user evaluation yielded positive results, and the glove effectively meets the users' needs, particularly in terms of usability.

The rigid parts from the second iteration were combined and made into a unified piece. By making it into a unified part that fits around the thumb, it became both smaller and easier for the user to put on and take off.

For the concepts of both the hand and thumb the intention was to let the wires run through tubes integrated in the material itself. Printing this type of construction in a FDM printer would fail as the channels would either be filled with support material or collapse, resulting in prototypes without channels and instead bigger sized tubes were glued in grooves to simulate the channels. This solution could however not withstand strong pulling in the wires, contributing to the prototype mainly being a tool for visualization.

The distal phalangeal part of the thumb construction showed better alignment to the body after the adjustments of the last iteration and the opening over the nail contributed to both airiness and a design more similar to the finger. However, there was still room for improvement in both sizing and conformation. Along the tip of the thumb the shape was still somewhat edgy which contributes to the prototype looking somewhat clumsy. Thereto, the thickness of the construction could be reduced for a lighter solution. The opening over the thumbnail was additionally requested to have a rounder shape in order to really mimic the contours of the nail. Nevertheless, the overall design still showed great potential for the intended purpose and further development.

The user evaluation of the concept showed promising results in regard to meeting the users' needs and wishes. The user could put on the glove independently and with an adjustment in the design of the wrist strap, possibly also lock the strap. The users were fascinated by the compact and sleek design of the entire glove. Both expressed high hopes that this prototype could eventually evolve into a similar finished product. The users appreciated that a significant portion of their hand was not covered, allowing them to retain their sense of touch. They described it as appreciative that they could still hold their child's hand or pet their dog and feel the sensation instead of constantly having their hand enclosed in a full glove. As the glove is meant to be worn throughout the entire day, this design consideration acknowledges the importance of preserving tactile sensitivity and maintaining a sense of connection with the environment, promoting a more natural and fulfilling user experience.

Certain improvements regarding the strap and positioning of the plastic tube on the wrist needed further examination in order to optimize the product's usability. The strap aspects played a significant role in ensuring a comfortable fit, allowing users to easily put on and adjust the glove according to their specific needs. Regarding the plastic tubes at the wrist, it was necessary to consider this as a customizable detail based on different users. This aspect, as well as the positioning of the strap higher up the arm, was highlighted during the live interview. The user mentioned using the outer side of their hand to brake their wheelchair, which could potentially be obstructed by the wristband and tubes. However, it was important to note that not all users may have the same preferences or techniques. Therefore, allowing the option to switch the side of the tubes and adjust the positioning of the wristband, using longer elastic bands, could enable the glove to be customized for different users' specific needs and preferences. By addressing these areas, the overall usability and satisfaction of the product could be enhanced, making it more intuitive and convenient.

Overall, users provided input on the importance of easily replacing parts or materials that wear out quickly. This insight was deemed crucial in the design process as it emphasized the need for a higher usability and sustainable solution. By considering the replaceability of components, the glove could be designed to be more long-lasting, ensuring continuous functionality and minimizing downtime for the users.

If one imagines that the hard parts for this type of glove are made, for example, by molding based on 3D scans, it can be envisioned that it is very easy to customize them according to different hand sizes. This would ensure a high level of comfort for the product. In the longer term the design also offered the possibility to cover parts of the construction surfaces that are in contact with the skin in some kind of foam material for potential additional gentleness and softness, similar to certain orthoses.

7 Deliver

For the final concept a refinement of the rigid glove concept was done to address the issues presented in the evaluations and a new concept sketch was made.

7.1 Improvements

The guiding plastic tubes were altered to the inside of the arm, according to the user’s demand regarding potential issues when braking the wheelchair. The initial sidelong bands however remained in order to keep the hand part in place. This way the tubes could easily be rerouted along the bands, if that would suit any users better. Another alteration was that the wires in the final concept pass through the rigid material itself, so that the channels are not visible from the outside of the glove. In addition to a cleaner look and protected wires, it also offered a smooth surface facilitating grasping of objects against the palm.

7.2 Final concept

The idea of this concept is to customize the glove after a 3D scan of the user's hand to ensure a close and comfortable fit. This provides the possibility to place the thumb in an opposition position prior to scanning and by that provide the support for a proper thumb position, with no need for further thumb supporting details. The tendons and plastic tubes run through the material to maintain their fixed path and be protected.

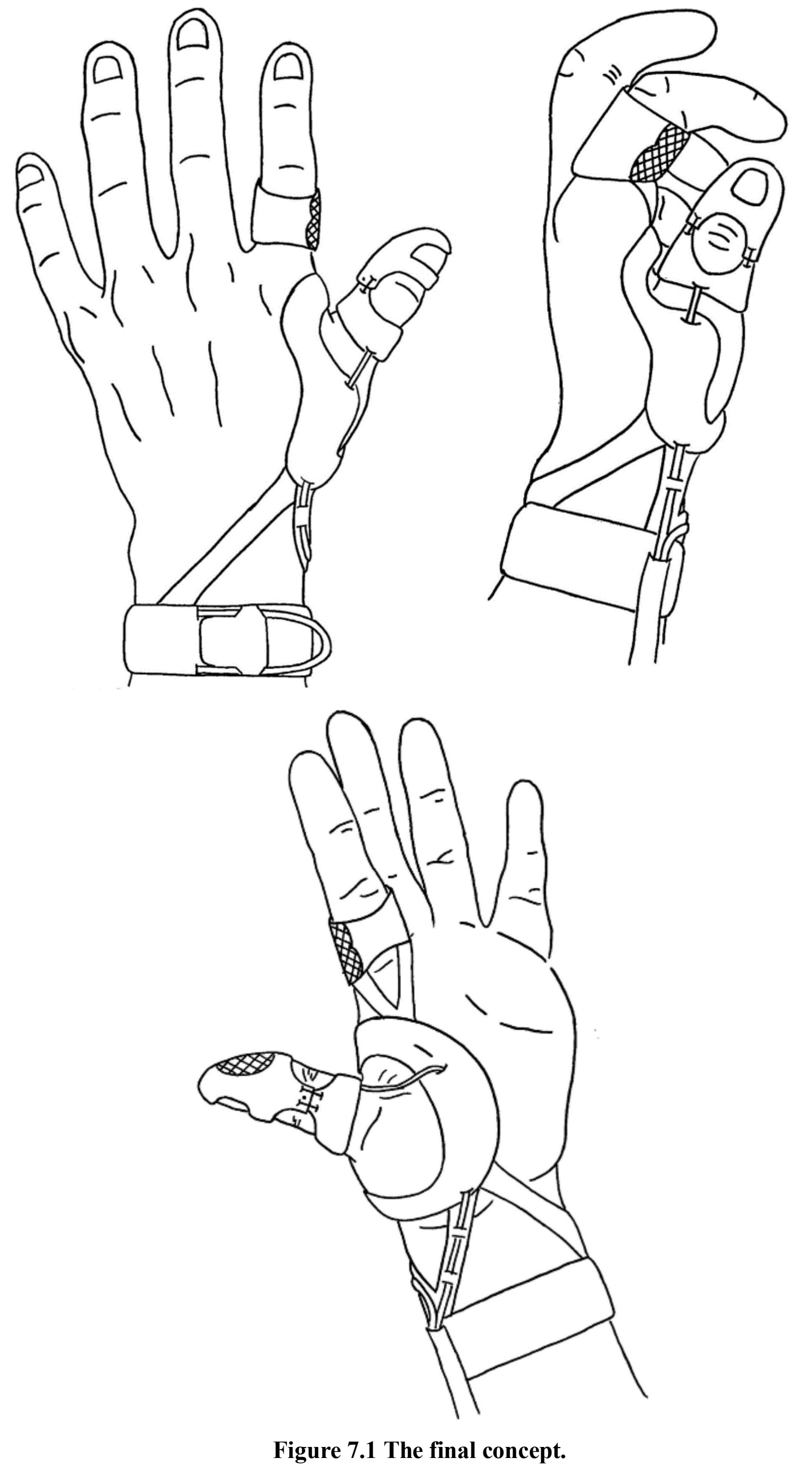


Figure 7.1 The final concept.

Material - The glove is based on a rigid plastic material, through which the plastic tubes run together with the artificial tendons. Their fixed position in the glove enables for an efficient force transmission. This material enables the user to easily and quickly wipe off and clean the glove which makes it well adapted to ADLs. This material also allows the user to customize the color of the glove.

Function - Friction pads are placed on the tip of the thumb and on the index finger locker but may also be attached on the lower thumb as well as on the inside of the hand. This friction material has a positive impact on the successful outcome of a grip, but also if the glove is worn when driving the wheelchair. This pad is meant to be replaceable as it wears out.

The fit -The glove is intended to be produced following a 3D scan of the users' hand to provide a comfortable and close fit.

Index finger - An additional index finger piece can be placed around the user's finger and then locked in position on the palm side of the glove. This part only covers the base of the index finger and provides an airy and easy design that allows the tip to move and retain skin sensation. If this part is used continuously, the idea is that it should be able to be put on the finger without having to be unlocked. The ability to open and remove the part is for those who sometimes prefer to have their finger free and mobile.

The strap - The strap is based on a silicon material and consists of a loop that enables the user to independently put on and take off the glove. The strap can be tightened by pulling in a loop at the end of the strap and then be secured by a magnet locker. The loop and magnet are both chosen to facilitate the use of the glove regardless of the user's hand function.

8 Discussion

In this final discussion, we will address overarching points regarding the final concept, methodology and the insights we have achieved with this project. More in-depth and detailed discussions about the project's various phases and iterations have already been covered in their corresponding sections.

8.1 The final concept

When applying the principles of universal-design, more specifically principle 1 - Equitable Use, with this design it aims to fulfill the principle of providing the same means of use for all users regardless of their abilities. The design has features such as a loop on the wrist strap to facilitate strapping and locking the strap. In addition, this concept is designed for easy put on and taking off, as the user only needs to slide their thumb in position, and then has the possibility to push on the thumb parts. Thus, no pulling is necessary, which is a more challenging motion for people with limited gripping function. As this design only covers a small portion of the hand and is intended to be manufactured in material that allows for different color options, this design can appeal to many different users.

The solution for the index finger has great potential. This solution is needed for certain users to keep the finger in place, while it can also be advantageous for all users as it adds extra friction due to its additional friction material. The solution we have proposed is not fully developed, defined, and evaluated. Due to time constrains, there was limited focus on the exact details for this part of the glove. The developed prototype has not been fully evaluated with users in terms of usability and in regard to the process of taking the piece on and off. Therefore, this solution may need further development and validation through user testing with a proper prototype.

We did not closely examine the exact placement of sensors, where and how it should be located. This decision was made based on advice from the company, as they indicated that the sensor technology may change in the future, and our design does not need to be specifically tailored to the current sensor.

8.2 User interactions

The interviews provided us with valuable information for the project and our development of a new concept. We obtained answers to the questions we had and by choosing to conduct semi-structured interviews, it allowed for further discussion on topics where either we or the user felt there was more to talk about. The early interviews with users helped us understand the daily life situations that could be challenging with a limited grip. The interview conducted at a user's home was particularly valuable as it allowed us to observe how different actions were performed with a limited grip. However, only three answers were collected in the questionnaire, including two of them from people who also had been interviewed. As the age span was the same for all- answers, 41-65, this contributes to a small demographic population and can therefore be biased. To reach out to more users, we could have employed various strategies such as advertising through different channels, reaching out to relevant communities or organizations, or utilizing social media platforms to widen our reach.

By involving users in evaluations even earlier in the process, it could have been a way to speed up the development phase. During the first iteration, users could have been invited to provide feedback on the different concepts, expressing any advantages or thoughts on how the concept would work in their ADLs. This early involvement would have allowed for valuable insights and enabled adjustments to be made based on user feedback, ultimately speeding up the development process.

8.3 Development

The separation of hand and thumb for parallel development, did open up possibilities to combine the various parts in several different ways, and find out which composition was most beneficial. Initially, the greatest focus was placed on the parts for the hand and thumb, covering the main functions of the glove. The remaining parts were worked on at a later stage when it was somewhat clear what the main parts for hand and thumb would look like. It was then easier to see how the strap, buckle and index finger fixation could be implemented in the best way. These were all important aspects for the maneuvering of the glove and with that the user independence in terms of the defined needs.

The prototypes made in this project were produced mainly as a concept visualization to be used in the process of evaluation with users. The access to materials and prototype production made it easy to build such physical representations. It was valuable to create prototypes at different stages of the development process. By doing so, we could understand how the materials would behave in the solution, and it allowed us to visualize our concepts more easily. The prototypes were especially valuable when presenting the concept to users. Through this process, we discovered aspects such as the optimal positioning of the strap on the forearm to avoid interfering with wheelchair users who brake with their forearms. Creating prototypes also helped us understand how they would feel when moving the hand or arm.

A great challenge in this project was to ensure that a new design still provides a satisfactory grip in regard to the mechanics. This aspect was not fully validated as no fully functioning prototype was manufactured. It would have been interesting to further investigate the functionality regarding the traction of the artificial tendons within the developed concept. If yet another iteration would have been done, the idea would have been to scale down the design more substantially and experiment more with the rigid material and see how the solution could have become neater. To make greater use of the emerging advantage of the material supporting itself. With access to other resources and manufacturing methods as well as greater competence in this regard, significant improvements to the prototype could be implemented. Regarding the hand part, it would first of all be about finding a solution where the passages of the wires are implemented in the construction and material itself, with no need for additional tubes. This would provide low friction as well as stability to the system of artificial tendons, which in turn would allow stronger pulling in the tendons and hence a more functional prototype. Moreover, it would most likely be possible to create a thinner construction than the current one and make adjustments to the shape and width of surfaces for further improved fit.

For the thumb, one could experiment more with the design of the construction by exploiting the material properties, and thus making it take up a smaller part of the thumb. It is mainly the surfaces between the wire passages and the gripping surface with friction that could be processed. Some surfaces and/or anchoring points could probably be made smaller, or even removed, without the structure collapsing or moving when properly implemented. Integrated wires and a thinner construction with improved body alignment would additionally contribute to greater functionality.

With functional prototypes, and the ability to create customized constructions, further in-depth user tests could be done evaluating the glove’s actual function and not mainly its design and appearance. All aspects of the grip could be observed such as force transmission and pulling of the wires, when paired with the remaining parts of Tendons product, i.e., the motor and sensor, as well as the positioning of the thumb and the overall gripping ability. Additional evaluations of the comfort and perceived feeling during use could also be obtained. It would provide important input in order to bring the prototype to the next step in the development process towards a finished product.

9 Conclusion

The aim of this study was to investigate how to redesign a robotic glove to better align with the users' preferences. To identify these specific preferences we conducted literature reviews, user testing, and interviews with both users and manufacturers of the product. We developed a concept for a new design of a robotic glove that closely matched the identified needs. By providing individuals with the means to regain control, combat feelings of helplessness, and promote a sense of empowerment, this innovative assistive technology opens new possibilities for improving the quality of life for individuals with cervical spinal cord injuries.

We have successfully designed a new concept for Tendo's assistive robotic glove - OneGrip. This concept provides higher usability and a more minimalist design. We developed this concept by gaining deep understanding and knowledge of the users' needs following close interaction with users, including interviews and observations. Through our contact with the users, we learned that a successful and appreciated assistive device should be easy to use, without being obstructive or inconvenient. Specifically for this type of glove, it is crucial that it is easy to keep clean following its use in ADLs and, most importantly, that it fits well on the user's hand and has the desired functionality. We also came to an understanding that independence does not only come when the glove is being used, but users also want to be able to independently put on and take off the glove.

In our literature research, we observed that there are various types of robotic gloves, both rigid linkage-based and fabric based soft robotic gloves, and these two categories have their respective advantages and disadvantages. Rigid linkage-based gloves have positive aspects when it comes to power transmission created by an external motor, while fabric-based soft robotic gloves are flexible and breathable against the skin. When looking at Tendo's two competing products in the market today, both of them are fabric-based. As the gripping motion is a very complex motion, it is challenging to achieve a natural thumb movement with artificial tendons. This type of product requires a great deal of customization, since all potential users will have different hand proportions and gripping abilities, and the glove needs to be fitted closely to enable a good grip.

Our final concept consists of a small and minimalistic glove made of a rigid material, with the activating artificial tendons running through channels in the material. This glove is intended to be manufactured based on a 3D scan of the user's hand to ensure a close and optimal fit. Manufacturing the glove in a rigid material, not only enables precise customization to the user's hand, but it is also a material that is easy to keep clean during ADLs. Additionally, it allows the artificial tendons to move freely without friction along a fixed path. Using a rigid material also enables for a smaller design of the glove in such a way that takes up less space on the hand. This is because the strength of the solid material requires fewer attachment points to keep it in place. The glove concept is adapted to the users' limited grip strength, incorporating additional loops and magnetic buckles to facilitate easier handling. The user tests conducted with our prototype have shown positive results and feedback from the users, regarding the design and additional adaptation to their gripping limitations. One user had the opportunity to test the prototype and managed to successfully put it on and take it off independently.

With this project we have contributed to Tendos mission of improving the quality of life for individuals with disabilities, through innovative assistive devices by diving deeper into the users' wishes and needs. To the company, Tendo, we wish to showcase the possibilities that come with manufacturing a glove using rigid material with channels for the artificial tendons. We want to share the positive responses received from users regarding the appearance, intended functionality, and further possibilities of our concept. Regarding further possibilities of the concept, we see a request that emerged from one of our users to attach additional fingers to the rigid hand part. We also want to emphasize and highlight the importance of early and close contact with users in the development of a customized medical aid. We have observed differences within the user group, including preferences, needs, and expectations regarding the functionality of a robotic glove. Therefore, we recommend that the company conduct broader, and more in-depth user studies. As rehabilitation engineering continues to push boundaries and prioritize user-centered design, the robotic glove stands as a remarkable example of how technology can be harnessed to create positive and meaningful impact in the lives of those with disabilities. The full potential of the concept developed in this thesis, the main glove and its associated parts, needs to be further explored and validated through manufacturing of a functional prototype, in a material that is approved for medical use, based on additional user studies involving focus groups or field trials.

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Appendices

Appendix A Defined need statements

The following section contains the template where the raw data gathered from the Discover phase was interpreted into need statements, described in section 5.1. The results can be seen in table A.1.

A.1 Need statement template

Table A.1 Statements from research data converted into numbered need statements.

Statement	*Need statement*	*Need no.*
Designs similar to stereotypical medical tools can lead to stigma and is a constant reminder of the injury.	The solution is aesthetically pleasing in its appearance.	1
Do not want an aid to attract attention and be conspicuous.	The device is discrete and neutral in its appearance.	2
"It should be invisible or neat."	The device is aesthetically pleasing.	3
By minimizing the gaps between device and user, the aid might feel more like a part of the user's own body.	The shape of the glove is well adapted to the user's hand.	4
	The glove feels compliant on the hand.	5
The current glove is somewhat big and clumsy.	The solution aims for a neater and more minimalistic design, with necessary details only.	6
The glove needs to be easy to put on as the users have limited strength and flexibility in their hands	The glove can easily be put on and taken off.	7
	Measures are taken so that the user can handle the device on its own.	8
Ease of use is an important aspect.	The glove/device is easy to maneuver.	9

Heavy weighted devices limit portability.	The device is effortlessly portable.	10
	The glove is light weighted.	11
Some users maneuver their wheelchair by hand.	The glove can be used while maneuvering a wheelchair.	12
The users should not hurt themselves in any way when using the glove.	The glove is safe to wear and use.	13
	The device is kind to joints in fingers/hand/wrist.	14
Some users have little to no skin sensation in the hands resulting in a higher risk of abrasions or pressure wounds as a result of lack of sensation.	The interaction between the glove and skin is safe and gentle.	15
	The surface towards the skin is smooth and aligns well with the skin surface.	16
The glove is not just for temporary use during some occasions of the day, but for keeping on during most of the day.	The glove is comfortable and can be worn for a longer period of time with no problem.	17
Heat and extensive sweating may cause friction towards the skin.	The construction is airy or has a breathable material.	18
The users will have the glove on throughout the day in many different situations so the material should be strong and resistant and not too heavy.	The glove is flexible.	19
	The glove has high durability. It can resist high wear and tear.	20
The current glove is not suitable for contact with water, the fabric gets wet and takes time to dry. An extra glove is needed to change with. Having to take off the glove multiple times a day reduces the likelihood that it will be used.	The glove is suitable for contact with water. The material is water repellent or dries quickly.	21
The current way of washing the glove is by hand washing and then letting it air dry, which is not very effective and can't be done whenever.	The glove can easily and quickly be washed or wiped off.	22
	The glove material beneficially tolerates disinfectant or other detergent.	23

The tendons will open and close the grip multiple times through the day resulting in a lot of pulling in the material so it has to be a strong material to not wear out too quickly.	The glove material is strong and durable.	24
	The glove is designed to reduce/avoid unnecessary scraping or wear and tear.	25
The users are utilizing the tenodesis grip.	The glove is designed to assist and enhance strength in the tenodesis-grip	26
	It is possible to bend the wrist in order to utilize the tenodesis grip.	27
The current solution only includes the thumb, however the index finger is held fixed in a flexed position.	The glove is assisting in opening and closing (extension/flexion) of the thumb.	28
	The gloves design enables locking the index finger in a closed flexed position.	29
It is mainly about the mechanics in the thumb, grip strength is needed but most challenging is to keep the right position of the thumb to get the correct mechanical grip, force generation and force direction.	The placement of wires in the glove is optimal in order to result in a correct gripping motion.	30
	The thumb is kept in place, in a suitable opposition placement.	31
	During flexion of the thumb it ends up in the middle lateral side of the fixed/flexed index finger.	32
It is important to think about the behavior of the inactive wires and materials.	Wires and material are implemented in a way so that when passive during a motion they are not getting in the way or get lumpy.	33
The tendons in the current design tend to drag or lift up the material and this movement in the material has a negative impact on the grip function.	The glove is as closely fitted on the hand as possible and stays that way even during motion.	34
There are critical points where the tubes have to be fixed for the gripping motion to become correct.	The glove includes several fixed points for the tendons that do not move.	35

The friction between the grasped subject and the fingers is crucial to the grip and provides better control in the grip.	The solution enables friction between the user and grasped subject. Reduces slipping.	36
A too sharp of an angle between the tubes outlet and the tendon may cause extensive wear or rapture of the tendon	The tubes in the glove are positioned in a way that does not cause unnecessary friction between themselves and the tendons.	37
It is important that the material is as close to the hand as possible with as little motion as possible, as motion in the fabric results in losses of pulling force.	The material of the glove contributes to or maintains optimal force distribution/transmission.	38
	The construction of the glove contributes to or maintains optimal force distribution/transmission.	39
More efficient force transmission with the tubes from arm/wrist to palm/back of hand being in one piece with no interruption. Will also be more durable due to no scrape of several tube ends.	Tubes for wires, from arm/wrist and up to palm/back of hand are placed to generate efficient force transmission and promote durability.	40
Wrongly integrated wires can overload the engine.	The tendons are placed and integrated in the glove in a way that reduces power losses and requires less power from the engine.	41
	Tendons are able to run without friction.	42
Today there is a second band below the wrist, to keep the base of the gathered wires in place.	The solution keeps wires and tubes gathered. No risk for getting entangled.	43

Appendix B Concept generation - sketches

In the following section a detailed description of the generated concept ideas, produced during the first iteration of development (section 6.2), is presented. Sketches together with listed information about each individual concept can be seen in figure B.1, B.2 and B.3 below.

B1. Concept sketches

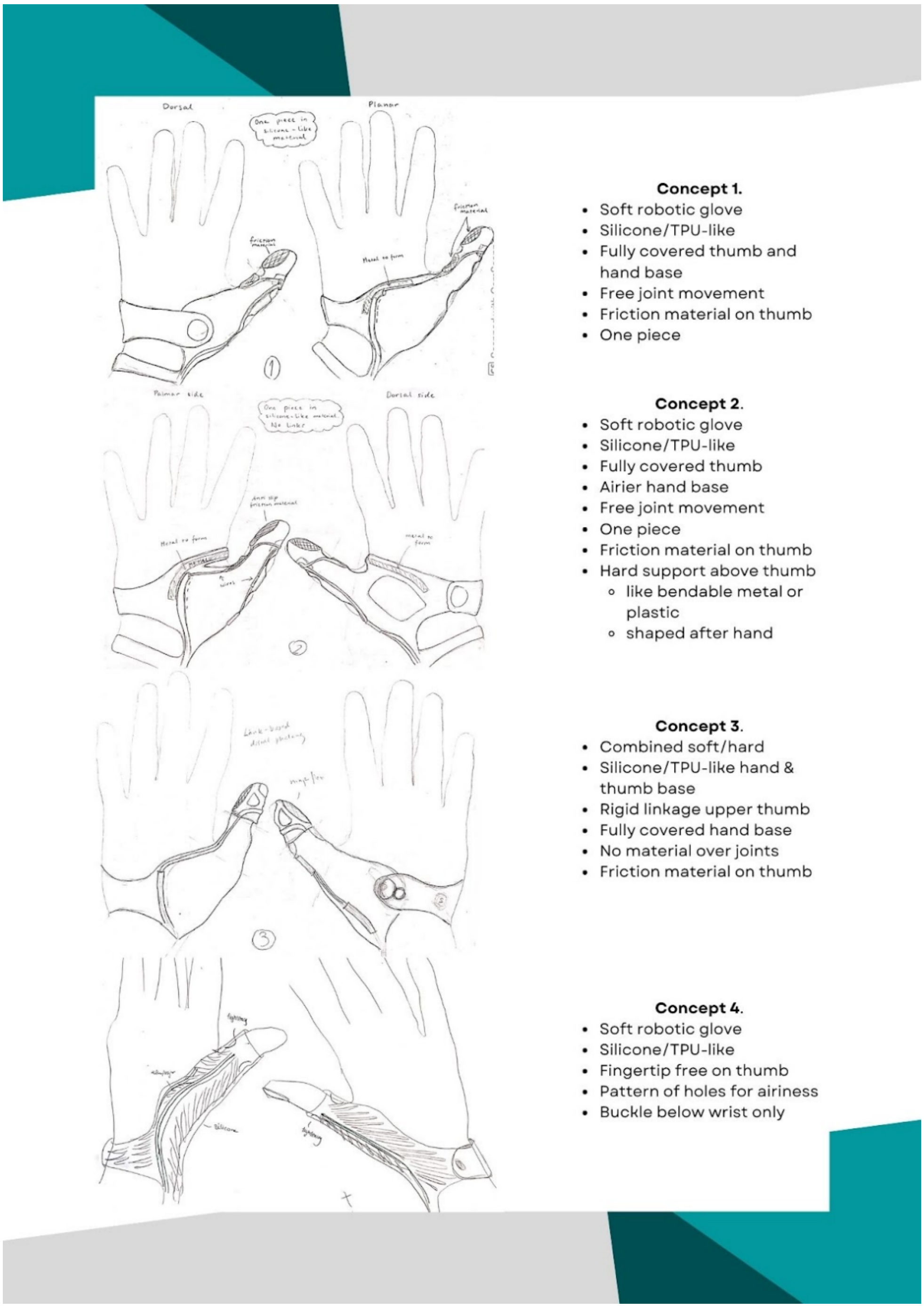

Figure B.1 Concept sketches with associated detailed information.

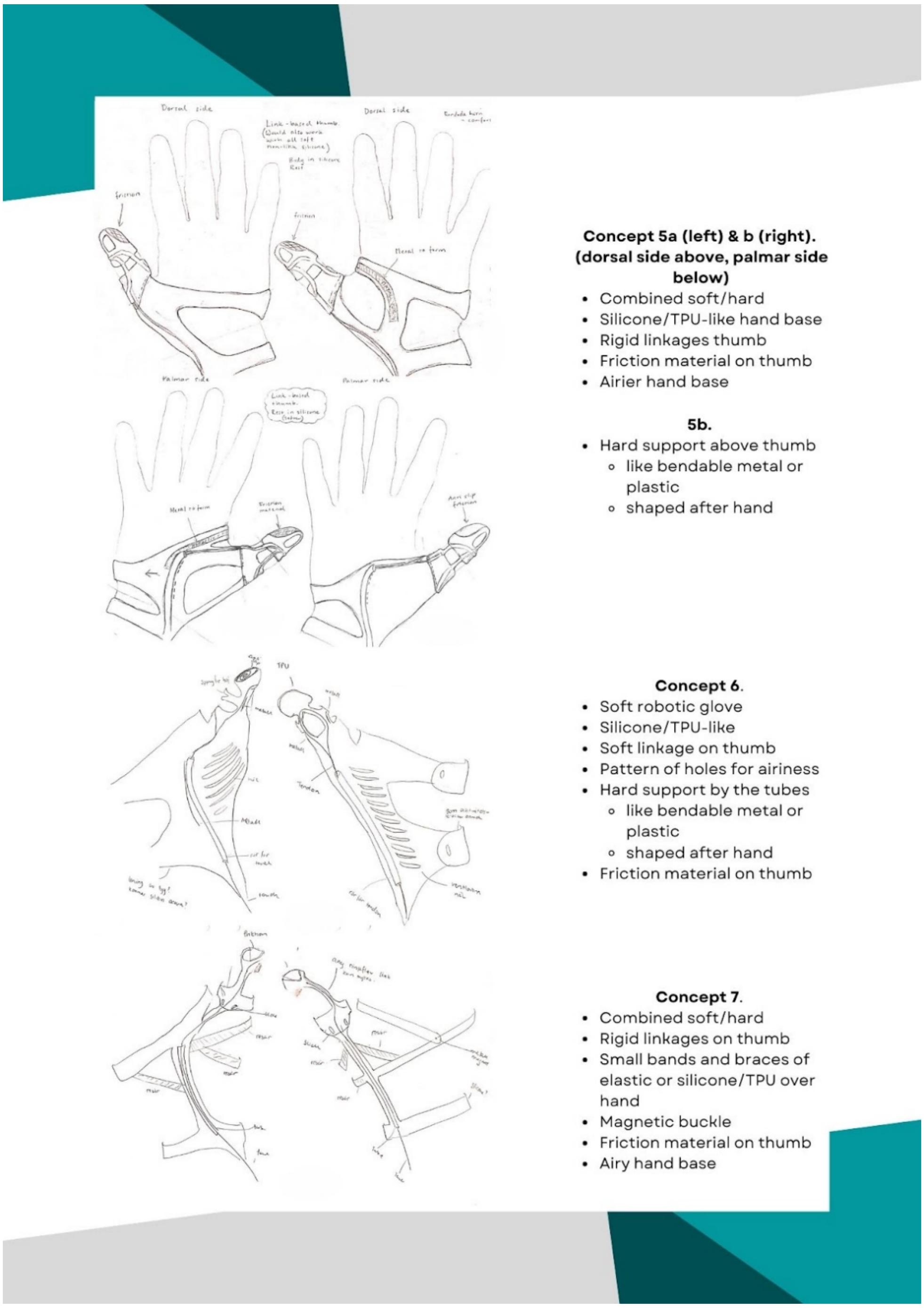

Figure B.2 Concept sketches with associated detailed information.

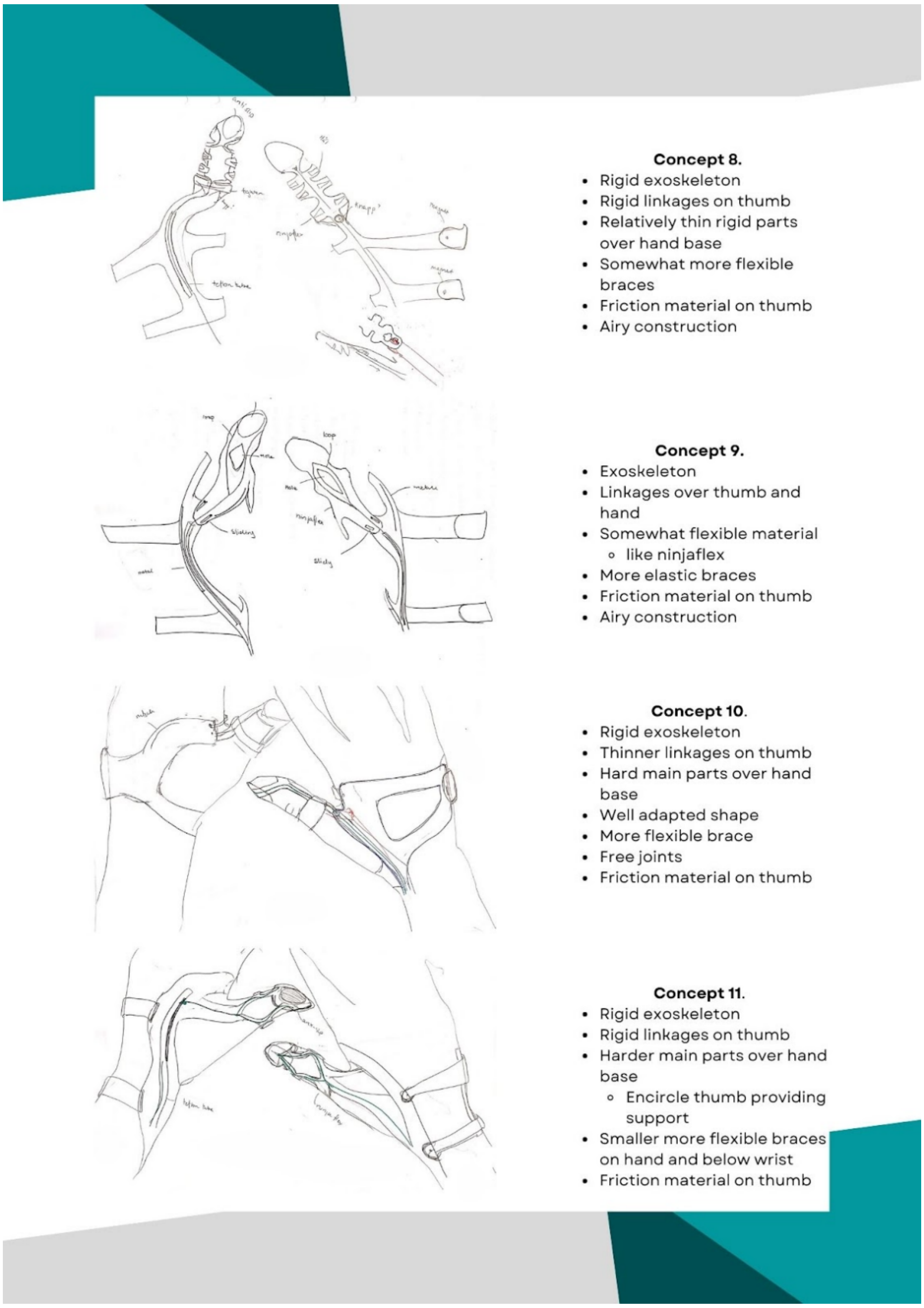

Figure B.3 Concept sketches with associated detailed information.