mōtus

Product report

Spring 2023
31st of May

Aalborg University

Industrial Design
Master's thesis

MA4-ID3

Danny Chau Huynh
Sofie Busch

title page

Aalborg University, Industrial Design
Create, Department of Architecture, Design and Media Technology

Title	**mōtus**
Theme	**Development of the EXOTIC exoskeleton arm**
Project team	**MA4-ID3** Danny Chau Huynh Sofie Busch
Project period	**1st of February 2023 - 31st of May 2023**
Main supervisor	**Christian Tollestrup**
Co-supervisor	**Jørgen Kepler**
Pages	**20**

abstract

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De eksisterende løsninger tilpasser sig ikke brugerens selvopfattelse og identitet, men tvinger dem til at efterleve deres præmisser. Exoskeletter bruges ikke af nydelse, men rettere af nødvendighed, hvilket tiltrækker uønsket opmærksomhed og minder brugeren om deres handicap.

mōtus er udarbejdet med henblik på at skabe et produkt, der lettere kan integreres i dagligdagen gennem en holistisk tilgang til exoskeletdesign. Ved at fokusere på individskabelse og tilpasningsmuligheder af udseendet, mens de essentielle funktioner er bibeholdt, skal mōtus blive en forlængelse af brugeren, både fysisk og emotionelt.

index

acknowledgements

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the paradox in the world of exoskeletons

Exoskeletons are artificial external structures that enable their users to perform actions they would not otherwise be able to by supporting movement and augmenting their natural capabilities. For many disabled, they are a necessity to perform essential everyday tasks. It is a relatively new market with constant technological progress, and is expected to become a more commonly seen product type in the upcoming decades.

However, with their current function-based approach, there has been little consideration to other factors needed to implement such products successfully into an everyday context. In this, there are several barriers but one of the largest and most noticeable challenges is creating a lasting and meaningful relationship between user and product. With the current design approach, the user needs to adapt to the exoskeleton with no possibility of customising it to fit their identity.

The bombastic design language draws unwanted attention in social settings and reminds the user of their disability. Paradoxically, despite being created to empower their users, exoskeletons have become a symbol of weakness and disability instead of one of independence and strength.

tetraplegics

Tetraplegia is the result of a spinal cord injury and is defined as a dysfunction of both sensory and motor function throughout the body. In the most severe cases, the vertebrae is completely severed causing complete paralysis from the injured vertebrae and down. However, more often than not, the tear is incomplete and presents itself as bodily weakness and varying degrees of loss of movement in the upper and lower body.

Every case is different but one of the most common consequences is the loss of strength and mobility in the hand and wrist area. **As the hand is tremendously vital to perform everyday tasks, the user becomes unable to function without aid or external help. As the condition strips the individual of their independence, they ultimately experience a feeling of being trapped in their own body.**

mōtus

mōtus is an exoskeleton glove aimed towards tetraplegics and other individuals with disabilities. While providing the essential functions to perform everyday tasks, mōtus offers a value that none of the existing exoskeleton products do - being a product that emphasises its user's identity instead of detracting from it.

Using a clothing-inspired approach to design, mōtus combines known technology with a minimalistic design language. The design seeks to embrace familiarity and resemblance to daily wear making it easy to integrate mōtus into an existing wardrobe rotation.

With a sleek design, the user can be confident that they will not look out of place wherever they go. The recognisability design and lifelike movements will surely bring back the user's independence and confidence in social contexts. Ultimately becoming a physical and emotional extension of its user.

an extension of the user's **personality**

To combat the current approach to exoskeleton design, mōtus focuses on enabling its user to find a combination of design elements that specifically match their identity and the way they want to present themselves.

The user will be given the choice to pick between a range of versatile colours for the different parts of mōtus. The colour palette was carefully selected to fit the Nordic customs in clothing, and contain both neutrals and vibrant nuances.

Besides colour choice, the user can choose between two braces, with varying densities in the pattern. This gives the user the freedom to switch between them to fit different occasions.

the anatomy

mōtus consists of four primary parts, each with their own distinct function. These functions were developed to support the user's lack of mobility but also to fit existing routines in an everyday context.

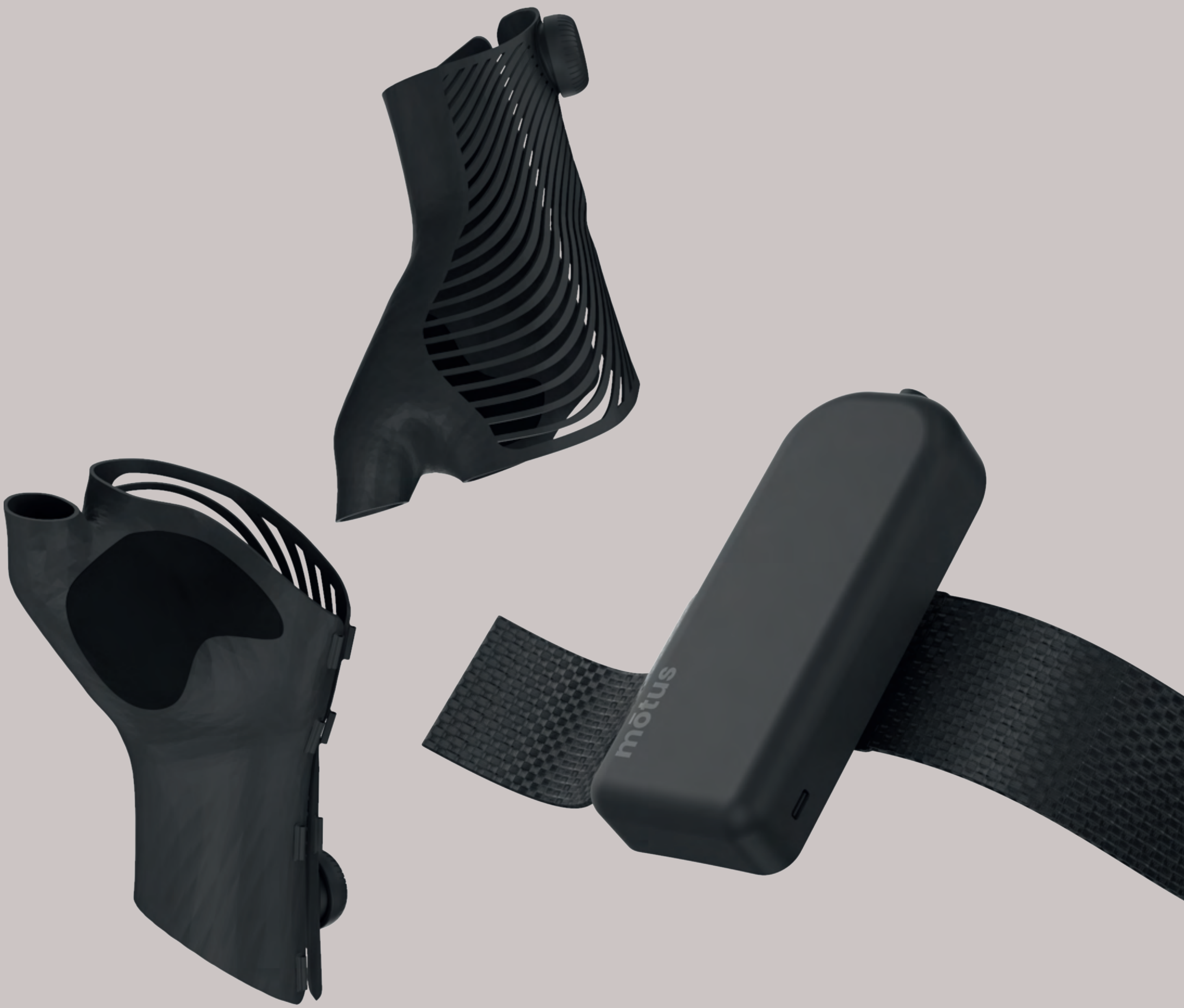
glove liner

The liner is the innermost layer and is in direct contact with the skin. The knitted properties makes the liner sit snugly yet comfortably on the user's hand. It acts like base layer clothing with superb breathability and moisture wicking properties that ensures comfort throughout an entire day. The liner is machine washable as to always provide the user's hand a hygienic environment to inhabit.

glove

The glove is layered on top of the liner. This glove contains the tendon cables that enable movement. Using snap buttons, the glove is easily connected to the brace to guarantee the desired fit. On the finger, there are silicone dots to increase friction when interacting with objects.

# of mōtus



brace

The brace is connected to the glove. Its primary function is to stabilise the wrist and put the thumb in an advantageous position to perform everyday tasks. Besides its functional purposes, the brace is also a large part of mōtus' visual identity. Using a wavy pattern it conveys the vision of movement and resembles the natural drape of clothing.

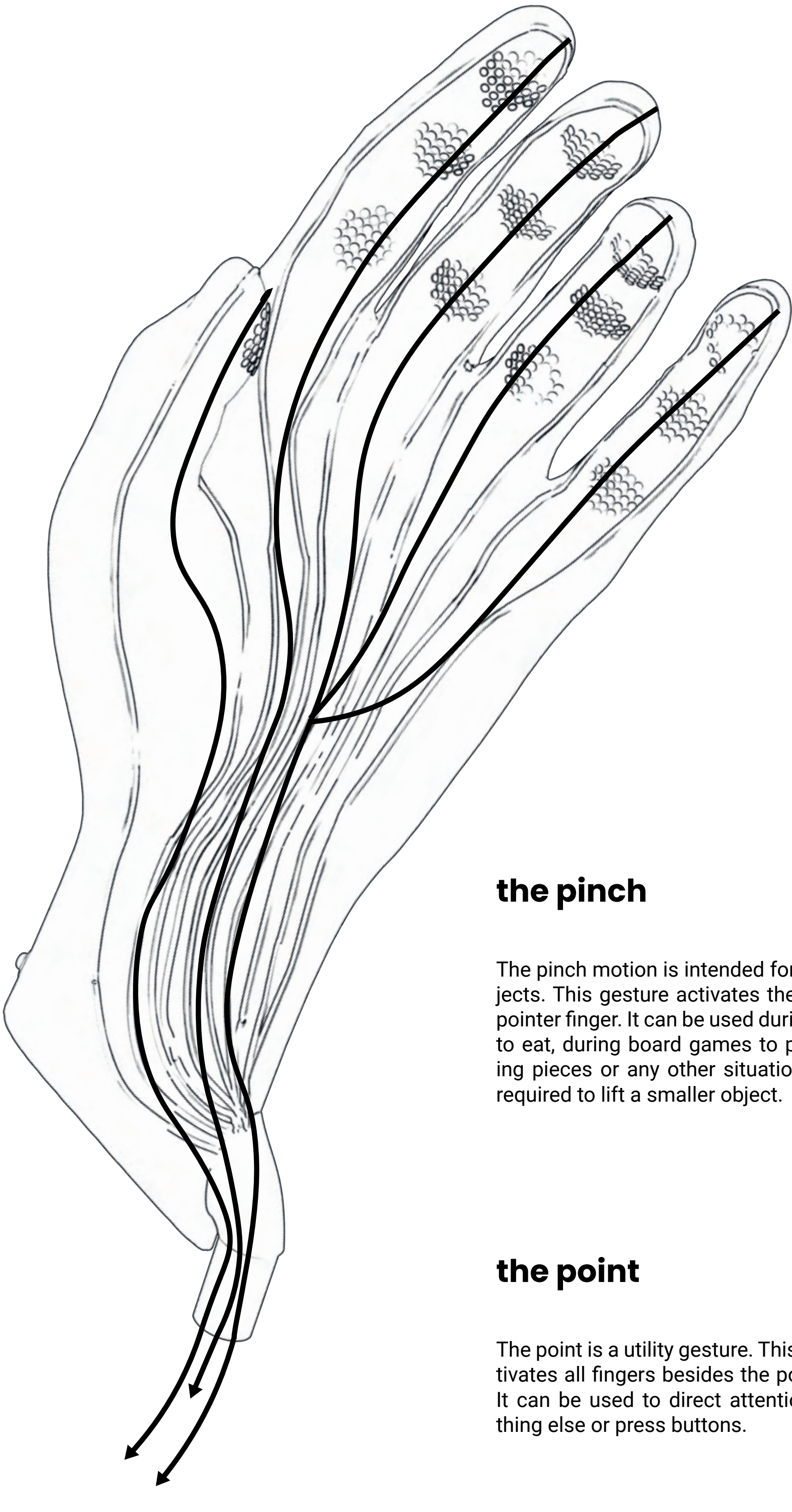
actuation module

The module contains electronic components such as motors and batteries that make mōtus work. Instead of having one set placement, the users are given the option to attach it wherever they see fit. The actuation modules should be attached to the upper arm.

the essential hand gestures

mōtus enables its user to perform three hand gestures: the grasp, the pinch and the point. **These gestures and a strength of 25N, allow the users to perform nearly all single-handed everyday tasks in an everyday context.**

The glove's agile movement is specifically developed to mimic natural movement so as to not draw attention to its user. mōtus actively enables movement in all fingers. However, the tendons in the middle, ring and pinky finger are connected to one motor and move synchronously to simplify the controls. The thumb and pointer have their own motors respectively.



the grasp

The grasping motion is intended for larger objects. This gesture produces the largest amount of force as it activates all five fingers. It can be used when handling larger objects such as coffee pots, cans and the like.

the pinch

The pinch motion is intended for smaller objects. This gesture activates the thumb and pointer finger. It can be used during snacking to eat, during board games to pick up playing pieces or any other situation when it is required to lift a smaller object.

the point

The point is a utility gesture. This gesture activates all fingers besides the pointer finger. It can be used to direct attention to something else or press buttons.

controls

mōtus can be connected to a variety of different interfaces depending on the user's disability level. What is similar for all of them is how the product is controlled.

When the user activates a gesture, the fingers will move accordingly as long as the user 'holds' the command.

When letting go of the command, the hand stays locked in the given position.

To release the gesture, the user simply activates a release command. Here the tendon cables return to their original position and strong woven elastics gently push the fingers back to a natural resting position.

integration into
daily routines

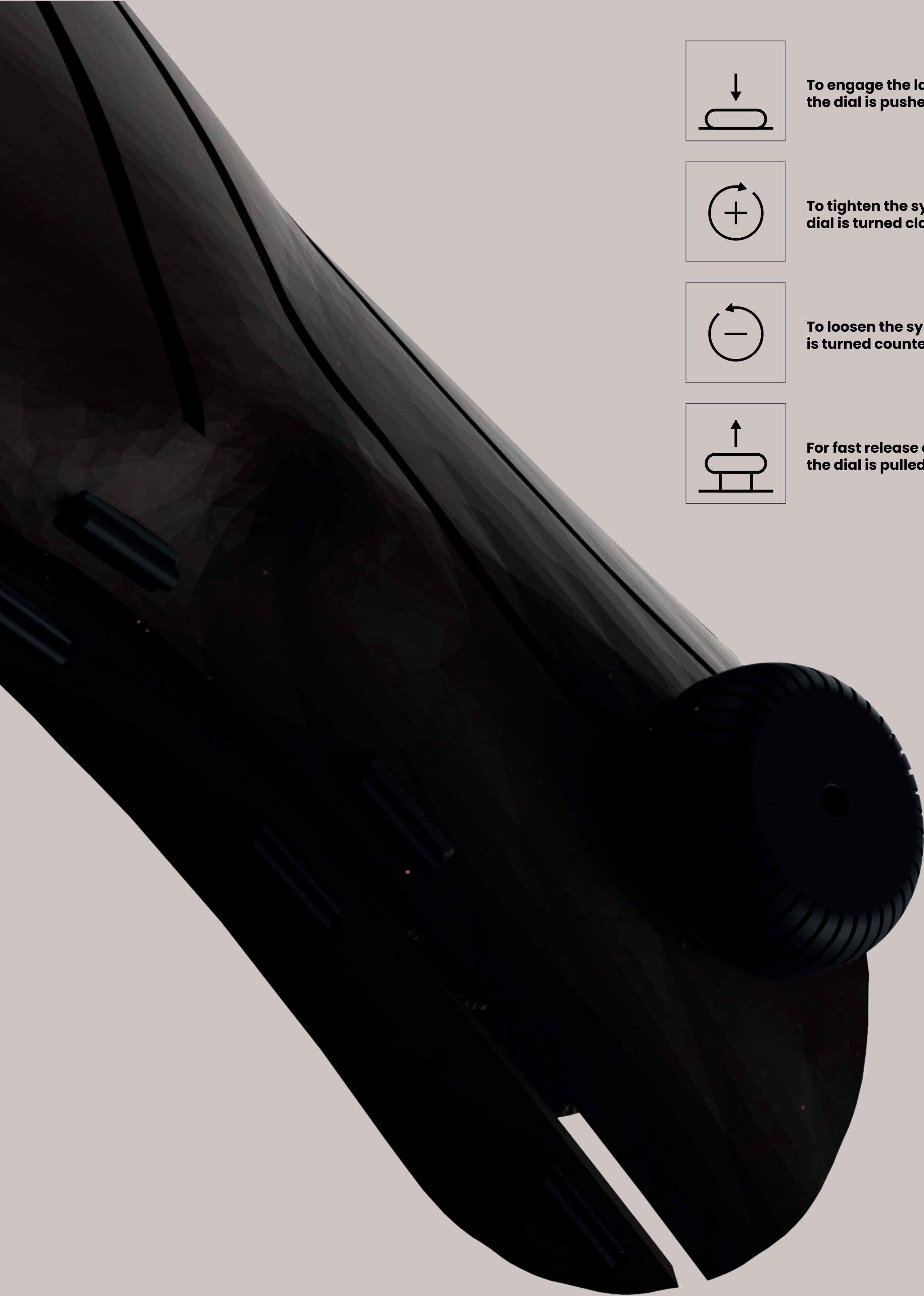
1. Place hand in the glove liner

2. Use the glove opening to easily don the glove

3. Put on the brace and tighten to

When donning mōtus, a cutout is made on the top of the hand to make it easier to put on the glove. This not only serves a functional purpose but also lets the colour of the liner shine through.

Not one size fits all. Therefore, a dial lace lock is used to tighten the brace and glove as needed on the forearm. The lacing easily lets the user tighten the product to their dimensions. This dial is placed on the outer of the brace.



To engage the lacing system, the dial is pushed down

To tighten the system, the dial is turned clockwise

To loosen the system, the dial is turned counter-clockwise

For fast release of the lacing, the dial is pulled upwards.

the fitting process

It is all-important that mōtus fits the user's hand as well as identity to a high degree. Therefore, when purchasing mōtus, the user will go through a few important sizing and customisation steps at a local dealer.

upon purchase, the user gets:

5 glove liners
1 outer glove
1 brace
1 actuation module

1: 3D-scan of the hand

To maximise effect and comfort, the brace will be based on a 3D-scan of the user's hand. As hands, wrists and fingers vary in length, breath and girth, these parameters will be adjusted accordingly.

2: glove sizing

After the 3D-scan, the user's hand is measured and a fitting size is chosen. Mōtus' sizing chart covers both liner and gloves, and therefore the user does not need to be measured twice. Based on the hand length and circumference, a corresponding size is found.

3: colour selection

The user will finally be able to choose a colour for the liner, glove and brace. Five liners are provided to fit a week's usage. By default, the glove and brace will be made in matching colours.

outer glove and brace colour selection

glove liner colour selection

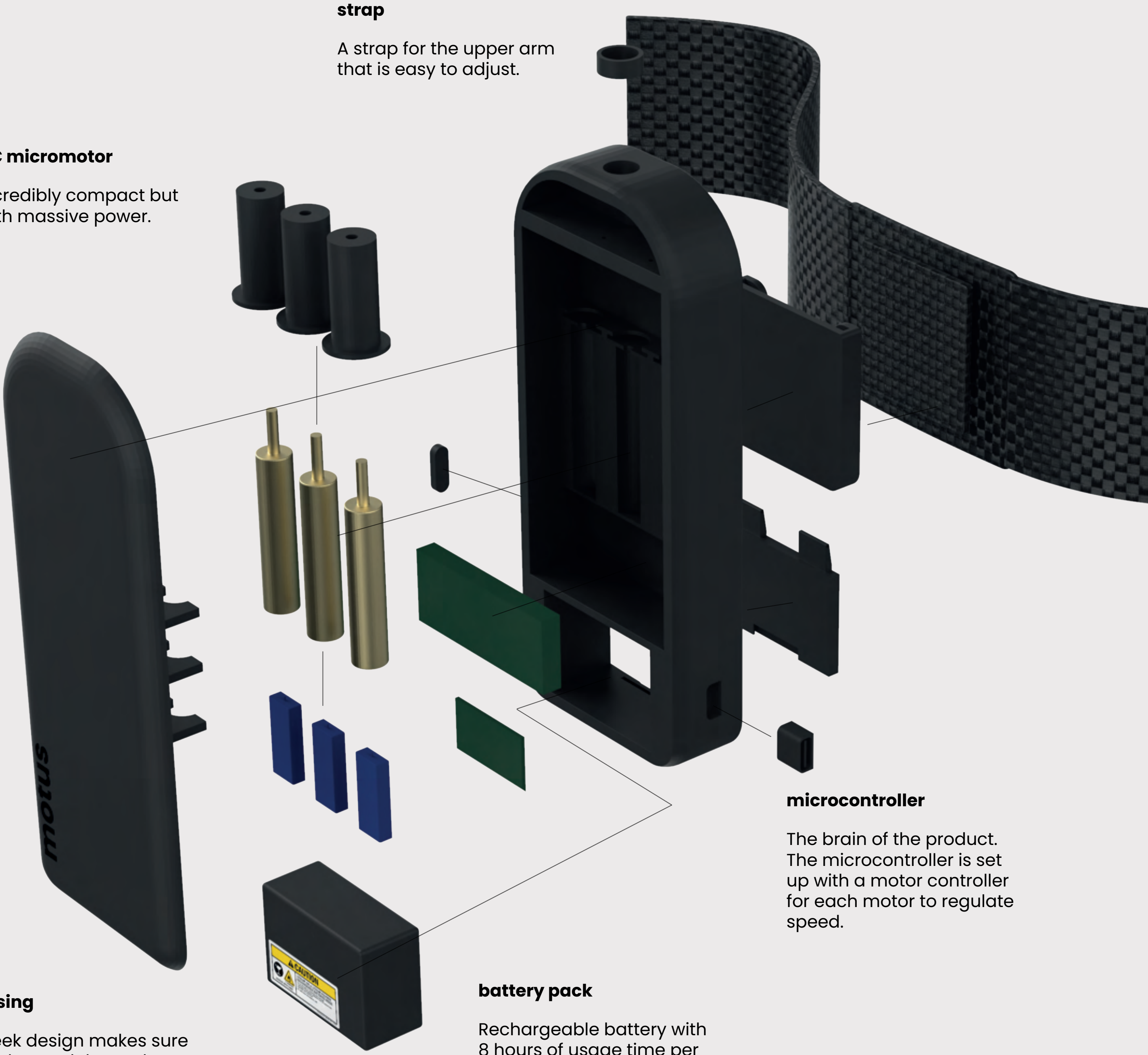
neutrals

vibrant

mōtus UNISEX sizing chart						
hand circumference (cm)	16 - 17,5	18,5 - 20	21,5 - 23	24 - 25,5	27 - 28,5	29 - 30,5
hand length (cm)	16 - 17	17 - 18	18 - 19	19 - 20	20 - 21	21 - 22

the construction

actuation module dimensions: 13,7 x 5,6 x 2,3 cm



strap

A strap for the upper arm that is easy to adjust.

DC micromotor

Incredibly compact but with massive power.

microcontroller

The brain of the product. The microcontroller is set up with a motor controller for each motor to regulate speed.

battery pack

Rechargeable battery with 8 hours of usage time per charge.

housing

A sleek design makes sure that the module can be worn under a jacket or bulky sweater.

dial lock

An intuitive tightening system that allows for easy adjustment throughout the day.

brace

3D-printed to match the user's individual measurements. The wavy pattern allows for the colour of the liner and the user's personality to shine through.

glove liner

A knitted liner in bamboo rayon guarantees comfort during an entire day's use. The smooth fabric is stretchy and machine washable for easy use.

glove

The COOLMAX polyester blend ensures a durable yet breathable construction. Using integral knitting, the glove has the right combination of a rigidity and stretch in all the right places to allow for great performance.

tendon cables

15x stronger than steel. The dyneema cables are used to pull the fingers in a lifelike and agile way.

implementation plan

Technical development

Continued development of the design and working principles, involving users. Special focus on fit, comfort and style, explored through rapid prototyping. Introduce a collaboration with robotic and software engineers for feasibility testing, and physiologists to ensure the safety of the user.

1

Funds and MVP

Funds will be sought from major companies supporting innovation in the medical sector. This endeavour will use a MVP to spread awareness of the project and spark interest form potential users and investors. Due to this, the production will be standalone with smaller compromises to the product.

2

Optimised development

Using the MVP along with advice from the initial users and expert stakeholders, mōtus is tested and developed further. All with the goal of collecting success stories through successful implementation into daily life.

3

First launch

The first launch will target 1% of the market to attain brand credibility through a proof of concepts. This launch only involves production of 100 units. Doing this, mōtus' market fit and user value can be determined by gauging the market response.

4

Optimise

Using the market response from the first launch, the second launch seeks to optimise production and increase user satisfaction through continued product development. Here, collaborations with external partners will be made to procure custom made components.

5

Second launch

The second launch will use an optimised production setup to achieve the intended function and appearance for mōtus. This entails an investment in new machinery and further strengthening user bonds through increased personalisation possibilities.

6

13.171 DKK per product	**22.000 DKK sales price**	**2.000.000 DKK initial start-up investment**

The sales price for mōtus is based on the existing market for exoskeleton gloves, focusing on establishing itself as a strong competitor at an unoccupied price range. The sales prices of 22.000 DKK positions itself to the more affordable end of the spectrum.

As there are two different production setups for mōtus depending on which stage the development inhabits, the breakeven point matches this. If only using the standalone production, breakeven would be reached after 117 sold units. However, as the plan is to optimise the production 100 units after the first launch, the breakeven point is reached after selling all 100 units from the standalone production and 28 units from the optimised setup.

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Introduction

Individuals with spinal cord injury tragically lose most of their independence in the blink of an eye. Tetraplegics, in particular, have lost their mobility in their lower body, arms and hands, which makes them highly dependable on their surroundings and relations. This often weighs on them and can reduce their quality of life and overall desire to participate in social and public settings. The growing development in robot technology and specifically upper body exoskeletons have provided the tetraplegics with a possibility to regain some of that lost independence. Unfortunately, we don't see many of the new market additions being bought and used in the desired manner, but rather that they are prone to end in the “valley of death” and be abandoned by the user. They do not fit the user values and demands or accommodate the use-scenario being the private and public space. A human-robot relationship is missing and should be defined, as well as a common language for implementing them in domestic life.

This master thesis will seek to explore how this can be done, and how the exoskeletons can get a stronger market position with the design concept mōtus. The main focus will be to develop a holistic design language which includes both the functional, applicationable, and aesthetic aspects. The combined design will offer an occasion based exoskeleton which, while providing increased independence, will adapt to the user identity and preference and become an extension of them.

Index

Reading guide

The documentation for this project is separated into four parts. The recommended reading order is as follows:
The product report which presents mōtus, an occasion-based exoskeleton glove.

The folder of technical drawings which present the product dimensions and specifications.

The process report which presents the process in its entirety.

The folder of appendices which contains additional material made throughout the process.

The process report documents the development of the process in eight phases: Scope, Understand, Function, Application, Aesthetics, Construction, Market and ultimately an Epilogue. Each phase, with the exception of Epilogue, ends with a design brief, a project overview and a reflection of the process so far. Throughout the process, boxes are used to highlight insights, criteria and other important information.

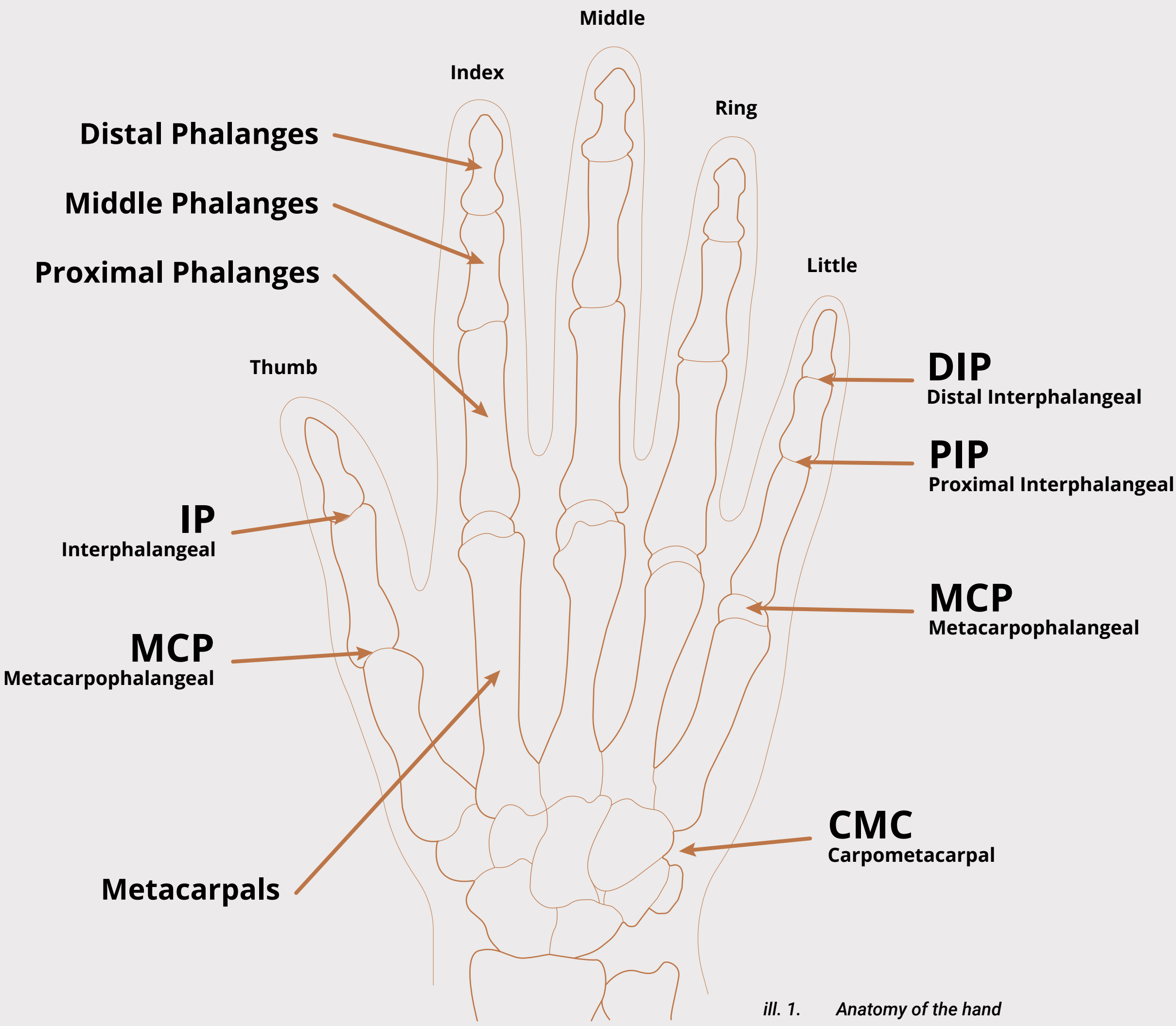
This is an insight.

This is a criteria. The criteria are numbered with "c#"

This is used to highlight information that is not an insight or a criteria.

Sources are referenced using the Harvard Method and references to information located in the Appendix are listed in-text as "(see apx. xx)".

Throughout the report, different technical terms for the anatomy of the hand will be used. These are illustrated below.



ill. 1. Anatomy of the hand

Scope: EXOTIC

Phase 1

This phase describes the point of entry of the thesis and the initial collaboration with REROB on the EXOTIC project. It uncovers the baseline of the EXOTIC project and mapping out possible targets wherein design knowledge could be applied. Assisting on the EXOTIC project was the initial aim of the thesis, but the team made a pivot which reasoning is also described in this phase. The knowledge acquired from the experts at REROB has nevertheless helped frame the project by sparking an interest within the team and setting the baseline for assistive wearable robotics on the market today.

Point of entry: An exoskeleton for people with SCI

Introduction: Establishing contact with the Neurorehabilitation Robotics and Engineering Group

Through an acquaintance from the AAU Design Lab, it was brought to the thesis team's attention that the Neurorehabilitation Robotics and Engineering Group (REROB) are currently developing an exoskeleton arm for individuals paralyzed in all four limbs - the EXOTIC (Thøgersen et al., 2022). It was mentioned during this conversation that the project, to this point in time, only focused on the exoskeleton's mechanical aspects and could benefit from a designerly viewpoint. This caused the thesis team's interest to peak.

ill. 2. The EXOTIC exoskeleton arm

What is the EXOTIC project?

Lotte N. S. Andreasen Struijk, is a professor and the Head of the Center for Rehabilitation Robotics. Mostafa Mohammadi, Post Doc, is occupied with developing the EXOTIC project

ill. 3. Lotte N. S. Andreasen Struijk & Mostafa Mohammadi

To gain a wider understanding of the EXOTIC project, its progress and goals, the thesis team established contact with Lotte N. S. Andreasen Struijk, Professor and Head of the Center for Rehabilitation Robotics, and Mostafa Mohammadi, Post Doc primarily occupied with the development of the EXOTIC. Beforehand the team read and discussed the scientific papers conducted by REROB about the EXOTIC. Questions were gathered from this, and brought to an online meeting with the REROB team. (see apx. 1) The meeting was structured as a casual interview where the goal was to start a discussion of potentials within the project with the interviewees.

The EXOTIC is an exoskeleton arm aimed at tetraplegics; severely disabled individuals with loss of mobility in all four limbs. The exoskeleton arm is based on a tongue-based control system (TCI) using novel technology allowing for precise control.

Through a virtual meeting, the thesis team was told a bit more about the EXOTIC team's ambitions for the upcoming years. The reason for the collaboration with the AAU Design Lab is to improve the overall user experience associated with the exoskeleton arm. In this, more resources, research and testing needed to be made in regards to the exterior, the mounting options and possible expansion of the market to more varied user segments. Lotte N. S. Andreasen Struijk describes the current state of the EXOTIC project as:

"Currently, the EXOTIC is like a car chassis with nothing covering it; there is no design. [...] How do we cover it, and how do we make it attractive for people to use?"

Conclusion

There was an opportunity to tap into the EXOTIC project as designers to develop the design and overall integration of the exoskeleton into a commercial market. The team was personally drawn towards this project and vision since it aims to highly enhance the life quality of a certain target group and addresses the power relationship and dilemma of wearing robotics as clothing.

In collaboration with Lotte and Mostafa, four main focus points were identified: Aesthetics; Mounting on the wheelchair; Comfort and Mounting on/off user.

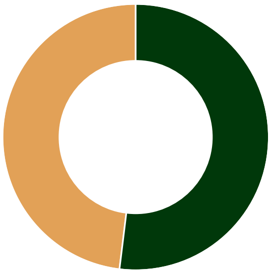
Spinal-cord injury and tetraplegia

Introduction

A desktop study was conducted to get a pre-understanding of spinal-cord injury (SCI) and the accompanying complications, early on. This consisted of both google-searches combined with research of medical-empiri and papers. The purpose was to align the target-group within the team, and furthermore identify criterias and early needs.

150
people in DK
&
18.000
people in the US

are hospitalized with SCI every year (Rigshospitalet, 2023; (Uab, 2023).



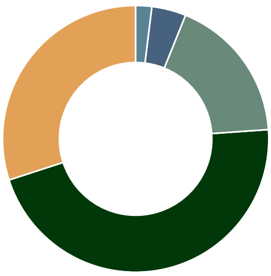
Traumatic SCI: 49,9%
Non-traumatic SCI: 52,1%

Traumatic SCI

Men: 72%
Women: 26%
Unknown gender: 2%

Non-traumatic SCI

Men: 55%
Women: 43%
Unknown gender: 2%



Unknown age: 2%
0-17 years: 4%
18-40 years: 17,8%
40-65: 46%
66 years and above: 30%

Spinal cord injury

While SCI is not one of the most common injuries, it is one of the most devastating for the injured and their relatives. (Cullan & Cullan, 2021) The spinal cord serves as the main communication pathway which transmits motor and sensory messages between the brain and the muscles, by peripheral nerves. In case of a SCI, these pathways are damaged by lesions. Because of this, the motor and sensory skills beyond/below the point of injury might be lost. Damaged neurons can not heal or regenerate themselves. Therefore recovery is dependent upon the number of spared neural pathways. However, the neural pathways are able to utilize the central nervous system to make adaptive changes and reorganize circuitry, which is called neuroplasticity. This means that some functions affected in the spine can be rewired to healthy areas of the spine, which is what is strengthened during a rehabilitation process. (Rehab, 2021)

SCI can be categorized into two types: Traumatic SCI and Non-Traumatic. Traumatic SCI is a result of an accident (typically traffic related or fall), non-traumatic is caused by disease or birth defect. statistics from National Spinal Cord Injury statistical Center from 2021 has shown that men in the age group 19-40 years old is the most common victim of SCI (National Spinal Cord Injury Statistical Center, 2021), however since the injury can happen to anyone, this project will not consider gender as a design criteria.

Tetraplegia

Tetraplegia affects the cervical area which is located near the neck, and everything from that particular vertebra and down. Their injury results in reduced function and the lack of motor and/or sensory functions in the affected areas, and more often than not, the inability to sense touch, pressure, temperature and pain (Klebine, 2023).

Individuals are affected to varying degrees depending on their injury but in a medical sense, there are two categories within tetraplegia to distinguish between (Rehab, 2021):

Complete tetraplegia
The spinal cord is completely severed, leaving the individual with complete paralysis from the affected vertebra and down.

Incomplete tetraplegia
The spinal cord is partially severed, leaving the individual with a combination of mixed function and paralysis from the affected vertebra and down. In these cases, neural pathways can utilise the central nervous system to make adaptive changes and rewire circuitry healthy areas of the spine.

The target group spans across genders and age.

Considers all genders from the legal age of 18.

Psychological effects of SCI

Besides physical limitations, the condition also places high demand on the individual's psychological adjustment. Several studies suggest that disabilities, in many cases, are linked to mental health issues and tendencies for anxiety, depression and abnormally high levels of negative psychological states.

"In studies (...) approximately 30% of persons with SCI in the rehabilitation phase were found to have abnormally high levels of negative psychological states."

(Craig, 2008)

"(...) studies suggest that approximately 25% of individuals with SCI experience clinically significant levels of anxiety whereas individuals who are acting as controls have significantly lower levels around 5%."

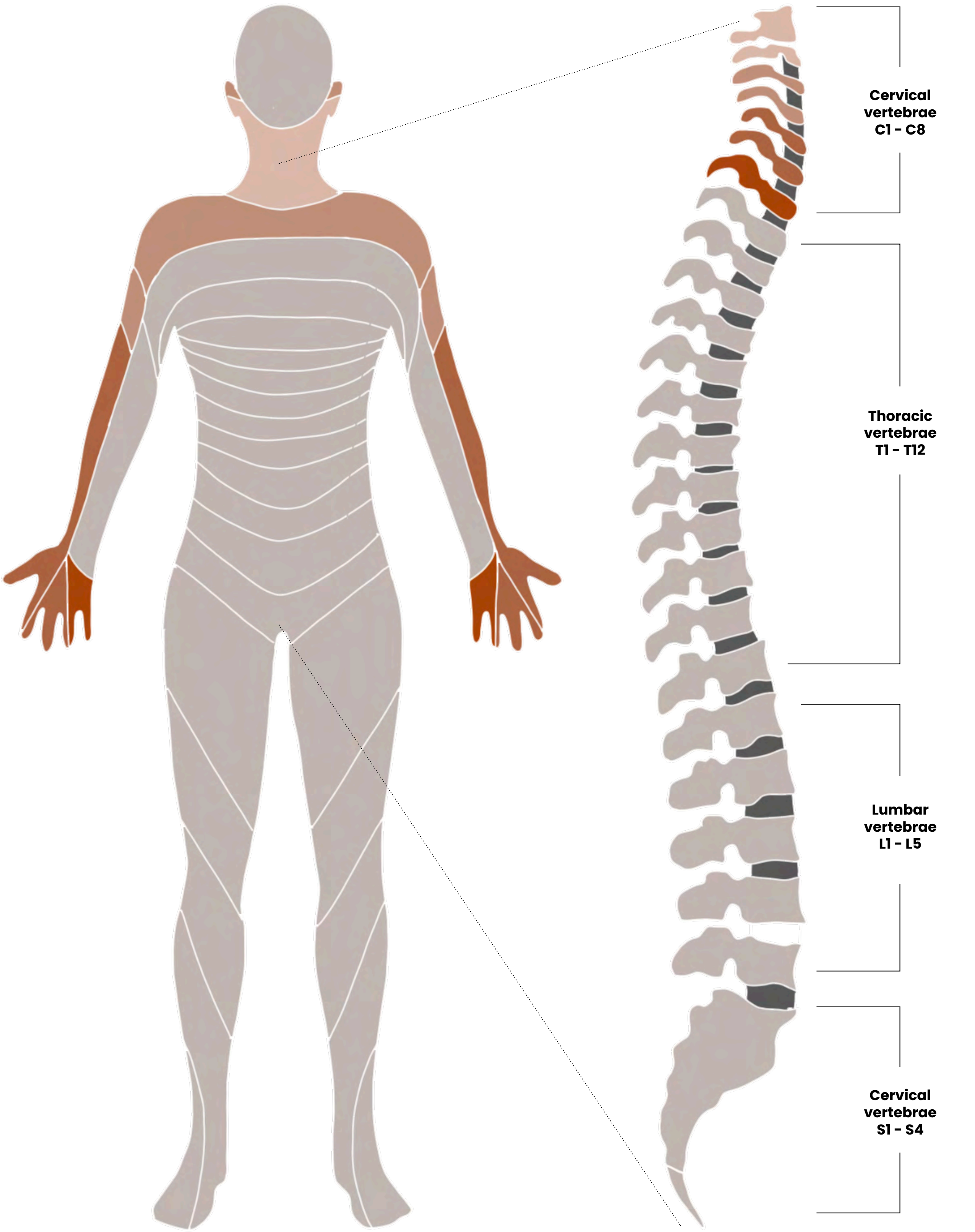
(North, 1999)

Another aspect, perhaps linked to the aforementioned, is the strain put upon family and personal relationships. The role of family member or spouse often turns to caretaker which forces them to act on new tasks, not previously required in the relationship – souring the 'power balance' and usually making the connection more of a chore rather than about enjoying the company of others (North, 1999a).

Dependency on others can put strain on relationships.

c1: The solution should be applicable across different genders and age.

c2: The solution should provide higher independency.



ill. 4. The spine

Conclusion

This study verified that a SCI and tetraplegia can happen to anyone, making the target-group quite broad. Furthermore the resulting loss of motion and sensory function can vary a lot depending on the specific injury placement and type, and benefits of the subsequent rehabilitation process. Because of this, there is already identified a potential need for designing a customizable product platform that can embrace a broader market of tetraplegics.

First two weeks
Baseline: Assistive wearable robotics

Introduction

In order to identify the specific entry point for this project and design perspective needed on the EXOTIC project, the team set out to understand the baseline and previous work done in the project. The aim was to understand the foundation and identify "holes" and potentials for redesign and/or further development. To do so the team combined desktop research, consulting expert-stakeholders, field research and testing at the EXOTIC lab. The methods included: Interviews (Cohen & Crabtree, 2006) and ethnographic field research (Sperschneider & Bagger, 2003).

Initial visits at the REROB lab

The first visit to the REROB Lab was to experience EXOTIC first hand, along with an informal interview (Cohen & Crabtree, 2006a) with Mostafa to gather more information on the project, its stakeholders and current design vision (see apx. 2). The second visit made it possible to try out the EXOTIC personally, which provided the team with first-hand experience of wearing and using an exoskeleton (see apx. 3).

Project status
The project is fast evolving but with a long end-date. Newer versions of the EXOTIC are already being considered and made, making the current prototype soon to be outdated. The user scope has been broadened to individuals with similar disabilities like ALS, but are struggling to find test subjects. The primary focus is now therefore improvement and optimization of EXOTIC.

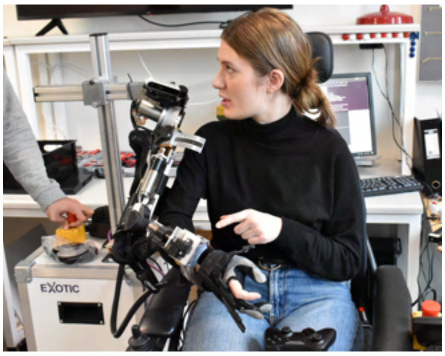
Current design criterias
The design is built on two main criterias: Strength and weight. The prototypes are developed and constructed by the Department of Materials and Production (MP) at AAU, and form, material and interfaces were based on these criteria.

The dream for EXOTIC
They aim to make EXOTIC simple and easy to use for the user with an optimised functionality. Asides from this, they wish to include a design that is pleasing to the users - but do not know how that is to be accomplished yet.

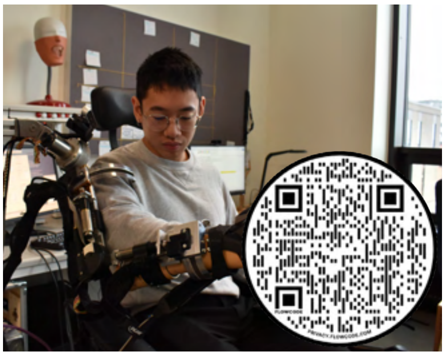
"The design should be smart, slim and simple. In general, something everybody would be pleased with."

Trying on EXOTIC
By trying on the exoskeleton it was possible to form a first-hand experience and map the feeling of wearing and controlling an exoskeleton. This way, the team could perform an acting-out (Sperschneider & Bagger, 2003a), and identified the following reflections on the experience:

Off-putting to wear.



Volume fit felt distant from the body.
Speed, of 4,5 cm/s felt okay, but looked odd.



First-person view, was intimidating and off.
The user feels locked, and the arm feels rigid.

ill. 5. Tyring on the EXOTIC

The design vision and development process does not correlate.

An exoskeleton is perceived as an extension of yourself.

Reflection: An extension of oneself

The team saw a potential to focus on the spiritual level and define a fitting valuevision for the EXOTIC, preferably accommodating the pleasing, slim and simple aspects from RERO, to tie in a holistic design. As an extension of oneself, there was a gap between the expected quality and the experienced quality. The connection to the exoskeleton-arm felt distant, and visible electronics seemed off on the body created association to rehabilitation and the medical field.

Interview with Frederik Victor Kobbelgaard

Frederik previously write his Phd thesis in collaboration with the REROB team. His thesis, “User Perspectives on Assistive Technologies” (Kobbelgaard, 2022), revolved around uncovering user needs for the EXOTIC project.

ill. 6. Frederik Victor Kobbelgaard

A meeting with Frederik Victor Kobbelgaard was established to discuss his PhD thesis, and uncover the users-aspects of the process and limitations behind EXOTIC. The meeting was executed as an unstructured interview (Cohen & Crabtree, 2006b) with bullet points as to what the team wished to discuss. (see apx. 4)

User involvement has been sparse throughout the project, and participatory design (Rosenzweig, 2015; Sperschneider & Bagger, 2003b) is a new addition to the process. Strategies as design games, focused interviews and user tests have been utilised to set the minimal user requirements to an exoskeleton for the upper body.

The essence of the results can be summed up:
- **They wanted the exoskeleton to serve in public and private settings**
- **The most important functions of the exoskeleton were: To drink, To snack, to itch oneself.**
- **The movement should feel and look as natural as possible.**

c3: The design must be fitted for the home-scenario.

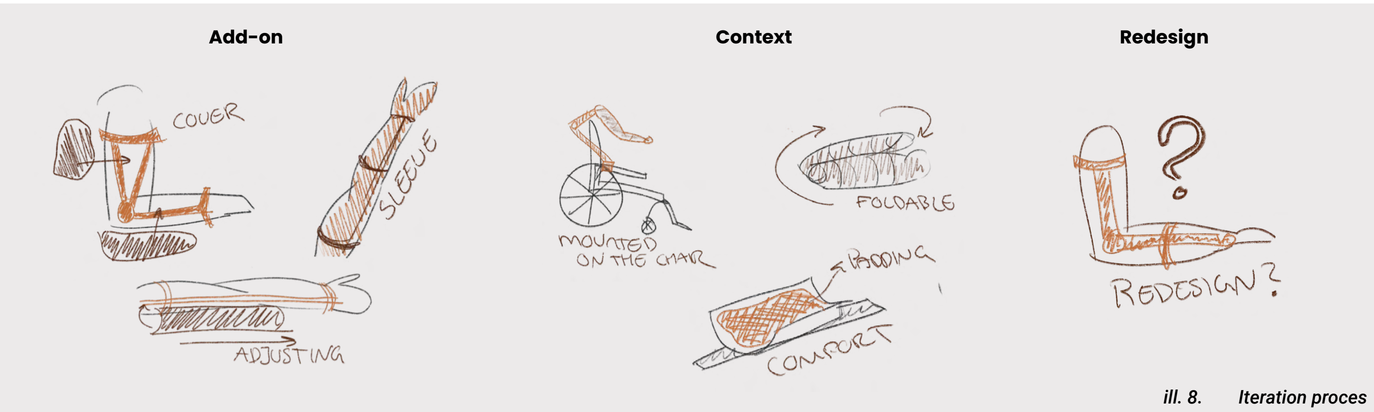
ill. 7. The most important functions

Reflection: Exoskeletons for everyday use

The EXOTIC project has taken a very technical and functional approach to user involvement. The team saw an opportunity regarding the day-to-day scenario. There was a possible conflict in designing both for the social and the private setting, as they might have different requirements, which is yet unexplored. Providing the users with basic manoeuvres is perceived as “bare minimum needs” but does not necessarily take into account the personal needs or implementation into an everyday-life. This is also relevant in regards to aesthetics, which was only addressed on a superficial level, and concluded that: It should not interfere and be mostly anonymous.

Iterate: Initial topics of interest

The insights and knowledge gained from the prior research topics led to an ideation process, wherein the team could identify possible themes and solution-spaces. This was done through brainstorming and a brainpool sketching session (Tollestrup, 2004). The ideas were visualised and clustered in categories (Tollestrup, 2004) (see apx. 5).



ill. 8. Iteration proces

Add-on
This introduces an add-on to the EXOTIC, which could be a hard case shell or soft cloth-like sleeve to drag around exotic to hide the mechanical parts, and bring association to clothing to make it blend into the wearer’s outfit. The vision would entail to make it less intimidating and enable the option for customization throughout different life-stages.

Context
This theme considers design for context with specific design dives. This includes mounting of the exoskeleton arm and portability on the wheelchair so that it won’t become intrusive or throw the weightbalance while driving it. Furthermore, an exploration of ensuring comfort through form and materials which considers the complications following SCI - for instance the risk of stroke or blood clots.

Redesign
This direction is meant to step away from EXOTIC as-is and challenge the construction through re-design, by considering a new holistic design strategy between function, construction and aesthetics.

Reflection: Lack of user feedback

The ideation process helped align the solution space and possibilities, however it was not possible to choose which features to pursue and create a feature hierarchy based on importance. The team needed to consult with potential users to determine the "fit" of EXOTIC into the domestic context and additional features and values to design towards.

Disclaimer: awaiting user response

At this point the team had been awaiting response from potential users, which unfortunately was harder than first anticipated. The product use-scenario and narrative for the context was missing at this point, and the team needed user involvement, to make qualified choices and move further in the project.

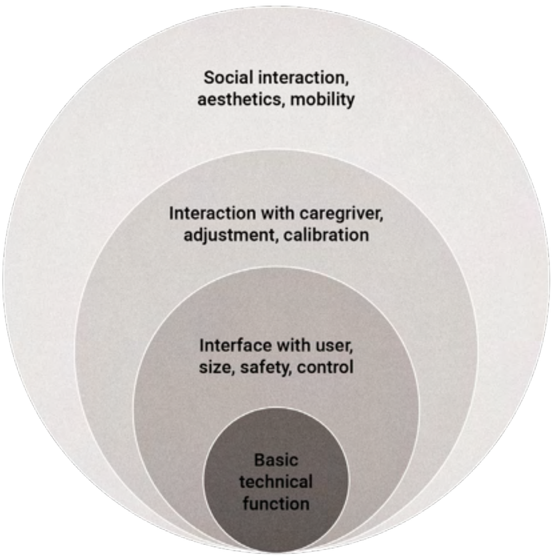
Rabbit Hole syndrome

Reframing focus

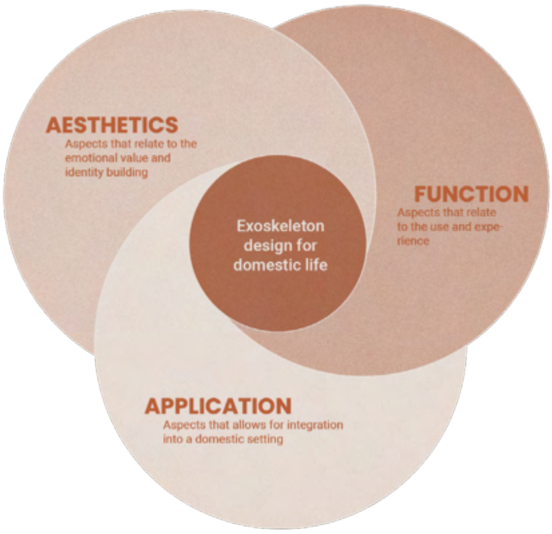
The initial project framing of assisting in the development of EXOTIC was at this point discarded and reframed.

The EXOTIC project was appealing to the team as a way to step into an unknown topic and product-sekement. It was highly interesting and motivating to help create a product-of-the-future with high potential and which addresses the robot vs. man dilemma. However, the team was blinded by this and overlooked the opportunity as design engineers to question the product itself, scope and the implementation strategy, resulting in design fixation and a rabbit hole syndrome. Knowledge of the EXOTIC project has provided valuable insights as a small case-study and will be used as such henceforth, and the REROB team as valuable experts on the field.

Along the way the team had developed alternative views on the project and desires for a design which would be more market-ready with a higher degree of emotional value. This drive made the team rescope the project, take a step back and look outside the box.
The team wanted to approach the topic and design of an upper-body exoskeleton in an alternative way: a new view on the holism between the different metal levels in the design. This was based on the findings during the first two weeks, and the team could narrow down the three main aspects to account for.



ill. 9. The correlation between design layers as perceived in the EXOTIC project.



ill. 10. The new correlation between the design aspects as perceived by the thesis team.

Holistic view

In the development of EXOTIC, the design aspects and hierarchy has been based on an onion-model and hierarchy-defined system, where the product has a clear independent core: Basic technical function (Thøgersen et al., 2022).
In this new definition, which encapsulates the design aspects for this thesis, will all aspects be valued equally with the assumption that one is not more redundant than the next. The hypothesis is that without a good use experience (function), domestic-life implementation considerations (application) or an emotional bond (aesthetics) the design would risk abandonment.

Understand

Phase 2

This phase focuses on establishing an understanding of the target group and their limitations when living with a spinal cord injury by uncovering needs and identifying opportunities within the field. To answer this, interviews, research and concept ideation was performed. This approach is taken to assist navigating the fuzzy front end of the project due to changing the framing and scope. The finds are summed-up in a project framing presented in a design brief.

User research

Introduction

User contact was established through the facebook group of RYK (association for SCI in Denmark) (RYKb, 2023), where two individuals reached out. (see apx. 6) The users were essential to understand the context and limitations for the product proposal to heed.

The contact consisted of an initial phone call followed by an interview with the users in their homes/workplace. This was conducted as a semi-structured interview (Cohen & Crabtree, 2006c) which allowed the interviewees the freedom to express their story, views and values. The results provided a qualitative but comparable data set of the two interviews (Cohen & Crabtree, 2006c). The framework of the interviews consisted of two parts; one regarding the user's context and experiences, and the other more specifically towards assistive wearable robotics in general with EXOTIC as case-example and point of reference. This would help the team define a feature hierarchy, deduct needs and values and the narrative for the product proposal. (see apx. 7 and 8)

The insights deducted from the interviews, showed both commonalities and differences between the two users, and the data was therefore analysed comparatively.

Lars Harder Tougård

Age: 26
Occupation: Bachelor's student in Machine Engineering

ill. 11. Lars Harder Tougård

- Tetraplegic (4 years), damaged c5 vertebrae.
- Paralyzed from the chest and down.
- Paralyzed in triceps, fingers, hands.
- Is able to lift arm and rotate wrist to some degree.
- Can not feel temperature but can feel touch.

Lars has a very sociable and active lifestyle. He participates in many activities and research projects and wants to assist where he can.

"It would be awesome to be able to drink a beer in a bar without aid."

Hanne Jespersen

Age: 60
Occupation: Early retirement due to her physical condition

ill. 12. Hanne Jespersen

- Tetraplegic (40 years) damaged c5 vertebrae
- Paralyzed from the chest and down.
- Paralyzed in triceps, fingers, hands.
- Is able to lift arm and rotate wrist to some degree
- No sensory function, has phantom pain.

Hanne has an active and independent lifestyle. She has many years of experience as a tetraplegic and has developed higher independence throughout the years.

"I would rather do the stuff myself, because then I'm sure it is done properly"

Cloak the disability & the 'inventor-gene'

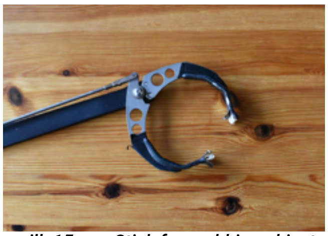
Both users are willing to buy more expensive assistive devices that look nice and ordinary, and do not appear as a tool for disabled. They will also go great lengths to research and find said items online, for instance a normal-looking bed or frame, smaller wheelchair or minimalistic bath-chair. Both have the inventor-gene, and have designed different tools as work-arounds, like cup-holders and special cutlery.

"I actually ought to have an electrical wheelchair, but I refuse to because then you look truly disabled"

"I think a lot of the assistive devices today are ugly. People who wear them look ill, and the devices are too much like a hospital device."

ill. 13. Lars in his wheelchair

ill. 14. Lars' cup (beer) holder



ill. 15. Stick for grabbing objects

ill. 16. Specialised computer mouse

Users aim to not appear too disabled.

Users are willing to pay for the 'right' tools.

Fluency in the routines

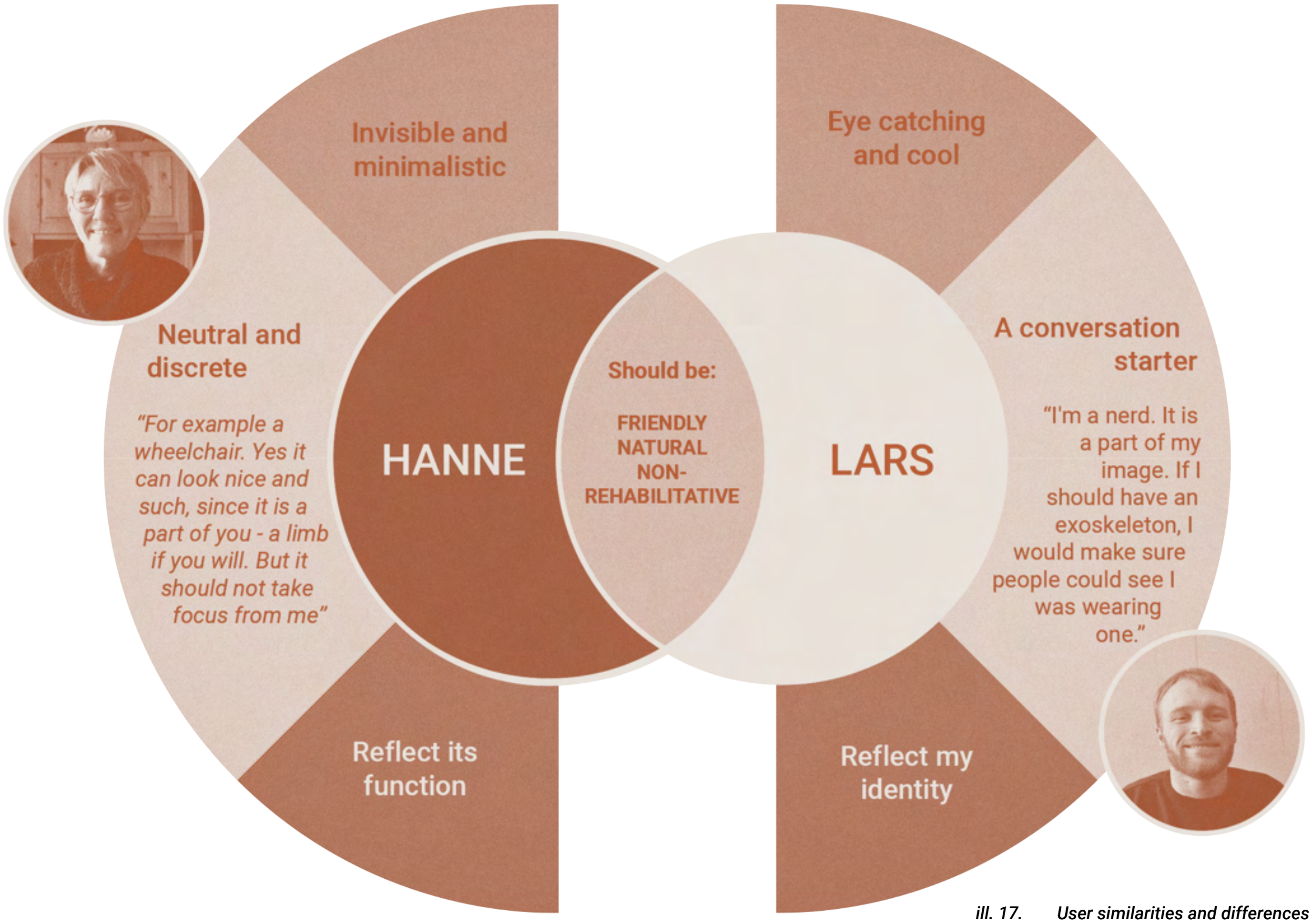
They have established routines and ways of doing things, they have adapted over time. The product must not get in the way of this and add too many extra steps in a day. This is both in regard to wear-scenarios, don and doff time and dimension.

> ***"It would be perfect if you could simply put it on in the morning and then wear it all day long."***

- c4: Should not be removed too often in a day.
- c5: Should be fitted to and account for the wheelchair.
- c6: Should be lightweight.
- c7: Should take up minimum space.
- c8: Should be able to be worn under a jacket.

Style and image

The users put a lot of thought into the choise of assistive devices and how they affect the perception of them in public. Neither of the users wish to appear too disabled and would like to minimise the amount of assistive devices they use in a day. Especially equipment that creates association to hospitals or rehabilitation are frowned upon, and instead they opt for more neutral looking products, even though they might have a reduced functionality. This firsthand encounter with the products highly relies on the aesthetics and CMF design identity. The user has different views on the appearance of the product, including wishes for an 'invisible' design, and an identity-dominant design.



ill. 17. User similarities and differences

- c9: The design should dissociate from hospital/rehabilitation equipment.
- c10: The product should be fitted an individual user identity.
- The users do not want their personality hidden behind equipment.
- Design dilemma: It should could be a conversation starter BUT not remind them of their disability.

Use cases

On top of the three interactions defined in the EXOTIC project, the interviews highlighted additional use cases for the exoskeleton, which was strongly valued by the two interviewees. The option of drinking, snacking and itching - as defined by the EXOTIC studies - was presented to the interviewees as a matter of course and minimum abilities of the exoskeleton, and they were encouraged to identify additional personal preferences. These have been listed in the following five use cases.


Playing games

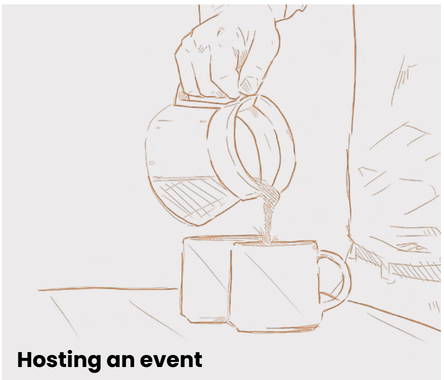

Out for a drink

"Perhaps I could make and serve coffee for my family more easily"

Reflection: What's next?
The hypothesis is that the user will get used to a functioning arm after a certain period of usage (coping time) - what will the next step be to provide value for the tetraplegic individual and how can this solution be adaptable to different user needs?


Paying for groceries


Cleaning


Hosting an event

ill. 18. Use case scenarios

Conclusion

The interview highlights the differentialities and common traits between the two users. Hanne and Lars are of different generations and personal preferences which makes them quite different but it is observed that they still share a range of common beliefs and values as tetraplegics in regard to their disability. Common for them is the desire to normalise and hide the assistive devices around them, and the willingness to go lengths to find and acquire these objects. However their views of style and product identity as well as the dream use scenarios vary noticeably.

The next step is therefore to explore overall which aspects of the design are intertwined and how to sequentially ideation on each. The first focus will be to explore the functional principles and how to enable the movements required for the scenarios described by both Hanne and Lars.

"There are a lot of things you have to do to which you need help, so anywhere you would be made independent would be.. I mean, if you can enable people to do something independently, you should."

Reflection: Aesthetics and product identity through customization

Views on aesthetics and product identity are different, which create a challenge in creating a design which would resonate with a broader user group across age and genders. This also leaves a potential to explore product identyíty through customization and tailoring the product to the users to increase the emotional value and enhance the feeling of the product becoming an extension of yourself.

Reflection: Market, adaptation period and first-movers

It is observed that there is an adaptation period which happens over time as the individual adapts to their new life situation and develops new habits to accommodate. Hanne is an example of a well-adapted individual with 40 years of experience, and Lars, with only 4 years as a tetraplegic, is less adapted. This shows as he is more willing to explore new methods and devices to improve his daily routines, whereas Hanne is more reluctant to change her habits.

This leads to an internal reflection on market entry and identification of the potential first-movers as the incomplete tetraplegics with a recent injury, who are still in the early adaption phase.

Userboard meeting

Introduction

As part of the collaboration with EXOTIC project, the thesis team participated in a user board meeting. The reasoning for participating was to obtain valuable insights in regards to available technology and research, as well as identify additional user needs and wishes when seeking to implement robotics into domestic-life.

As part of the collaboration with EXOTIC project, the thesis team participated in a user board meeting (see apx. 11). The reasoning for participating was to obtain valuable insights in regards to available technology and research, as well as identify additional user needs and wishes when seeking to implement robotics into domestic-life.

During this meeting, four tetraplegics participated, and will be kept anonymous.

ill. 19. *Members of the REROB team presenting at the userboard meeting*

Power-relationship
REROB presented multiple interfaces to implement into EXOTIC (EMG, TCI, BMI) This made the users reflect on the importance of self-initiated and controlled movement:

"You are involved and the initiator of the action, even though it might be semi automatic. It motivates you to use your own muscles and train and get better."
Tetraplegic, female, physiotherapist

All agreed, that upon seeing their own body moving caused great joy and motivation. But the users needed to be in full control to feel as the initiator (and owner). Too much automation would distance the user from the exo and uneven the power-relationship between the man and machine.

c11: The user should fully control the movement.

The importance of aesthetics
The users put a lot of weight on the appearance of the exoskeleton arm.

"30 years ago, my wheelchair was bright orange. Today it is grey. (...) I would want others to see me, the person, before they notice my wheelchair."
Tetraplegic, male

In addition to this statement, the partner of the user stated that she liked the idea of customization because it would allow her partner to 'dress up'. Just like with clothing, the user could switch parts and turn the exoskeleton arm into a dressy arm, a work arm or perhaps just a home arm.

"As the girlfriend, I personally think that it would be nice to apply a personal touch to the design".
Partner to tetraplegic, female

c12: The solution should be aesthetically customizable.

Independency
The users placed a lot of importance on being able to act independently, especially in a social context with friends or family. However, they did not want to eliminate the assistance of caretakers as they help with the most vital health-oriented needs.

The main focus of the exo should not be to enable complete independence, but rather make room for smaller pockets of opportunities where the user could manage tasks on their own.

The users can have up to 5 different caretakers throughout the week. Because of this the product needs to be simple and intuitive for multiple secondary users to manage it.

The solution should aim to enable independency in smaller scale.

Conlusion

The user interviews and participation in the userboard meeting provided valuable insight into the users daily life routines overall needs, along with wishes and fears in regard to owning and using an exoskeleton. It was made clear that the users would highly value an exoskeleton in social and public settings surrounding others. This would enable them to gain some independence alongside their peers and privacy from a potential caretaker. In regards to this, the appearance is valued as highly as the function, however the specific appearance criteria is remarkably individual and is defined by personal preference.

The next step in the process is to collect all insights to define a common vision and understanding of the product direction.

Design dilemma: The exoskeleton arm should be a personal extension of the user BUT not something they are defined by.

Framing the target group: Incomplete tetraplegics

Introduction

An upper body exoskeleton can benefit different user groups with different disabilities and mobility complications, which makes a huge potential for scaling the design proposal onto different areas. However, for this thesis, the case-group used will be incomplete tetraplegics.

After user contact was established with two users, it became evident that the prospect of collecting more users for feedback throughout the project was mostly out of sight, since it has proven particularly difficult to recruit further individuals who fit the requirements to the project. Because of this, Lars, Hanne and the individuals in the EXOTIC userboard will be the target group and their needs and wishes will set the direction of the project.

Incomplete tetraplegics also constitute 78% percent of all tetraplegics, as it is the most common type of SCI. This also broadens the market potential and validates including this target group as the focus in this thesis.

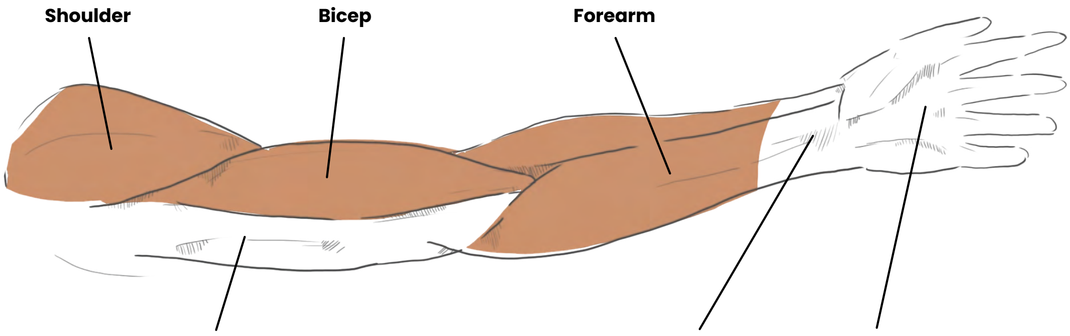
Benchmark for mobility

This chapter describes the restrictions of the user groups and the desired mobility level the product is expected to provide. It was necessary to define a benchmark for the natural mobility required for various applications throughout the day. To determine which actions to look into the team took point of entry in the iADL's instrumental activities of daily living. This analysis would help to define the number of gestures and motions to enable along with areas to avoid to actuate in risk of hindering the users natural mobility.

Users mobility restrictions
Using the conducted interviews and on-site observations, it became evident that the user group has varying degrees of functional mobility. It was made clear by Lars, who provided insights through his extensive network of other tetraplegics, that not one SCI is identical to another. They do not induce the exact same movement restrictions. However, in many cases, individuals with incomplete tetraplegia show the same restriction patterns, which was made evident by observing Lars and Hanne. There are two primary points that categorises the chosen user group:

- **Regained motor function in shoulders, forearms and biceps.**
- **Slight or no function in hands, wrists, and triceps.**

This means individuals from the user group are unable to extend their arms as well as properly use their hands. Looking specifically at the hand and wrist, the loss of motor functions usually leads to a weakened state and as a result the fingers can not produce sufficient grip strength and the wrist is limp.



ill. 20. Anatomy of the arm

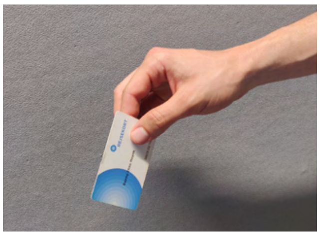
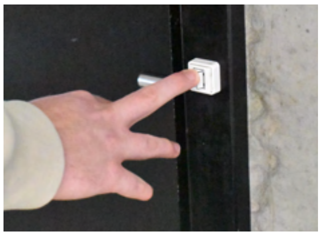
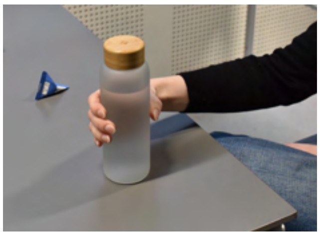
Instrumental activities of daily living (iADL)

Looking at what the desired state of mobility is, different relevant situations are identified with the purpose of testing and observing the movements. These situations were identified during the user interviews (see apx. 9 & 10) as well as the user board meeting (see apx. 11). The user interviews and userboard meeting made it evident that the users would like to be able to act independently when in social settings and contexts and enjoy their time with minimum assistance. However it was also learned that they highly relied on their caretakers and were uneasy with the idea to eliminate them and their vital function in their life.

The focus is therefore set on the iADL's as these refer to situations related to personal independent living tasks: socialising, hobbies, shopping, etc., and not the most basic needs: eating, drinking, health and hygiene related tasks, etc. as these are part of the basic ADL's. (Connected Home Care, 2018) Some activities may still overlap such as snacking and eating, but generally there is a clear distinction between the two categories (Andersen et al., 2015).

"People define themselves to a greater extent through involvement in iADL tasks, where the way the task is carried out can be varied according to desire, time and interest."
Translated from (Andersen et al., 2015)

To ensure repeatable tests and clear points of observation, the situations are explored further and translated into actions and finally specific mechanical principles with DOFs. The most common iADL's in various situations were chosen and others left out since they showcased similar actions. (see apx. 12)

Scenario	Action(s)	Motion
Shopping	• Taking item from shelf. • Typing pincode. • Carrying a bag with items.	 
Public transport	• Pushing stop-button. • Holding travelling-card.	 
Phone	• Holding it to the ear. • Pushing buttons on the screen. • Swiping.	 
Out with friends	• Snacking. • Holding cards. • Take a drink. • Handshake.	 
Hosting	• Opening door. • Serving coffee. • Petting child. • Handshake. • Point to something.	 

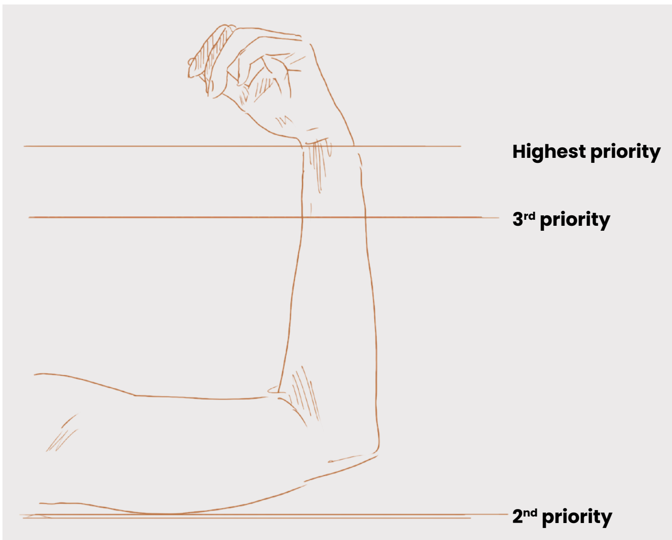
ill. 21. iADL table

Grip identification

Looking at the observed movement patterns from the baseline test, the motions can be split in a hierarchy of functions in which the hand is the most crucial to perform tasks (iADLs) and interact with the surroundings. Without the ability to use the fingers, moving the rest of the arm can produce unfruitful results in almost all everyday situations.

As observed during the test, it was discovered that three gestures were sufficient to perform mostly all activities. The three identified hand gestures are the grasp, the pinch and the point. Depending on the size, weight and shape of the object, the chosen action would vary accordingly. As stated by Cutkosky (1989), an object of smaller size typically requires an increase in dexterity, whereas a larger object requires an increase in power but less dexterity (Cutkosky, M.R., 1989).

Grasping, pinching and pointing enable an individual to perform nearly all daily tasks.

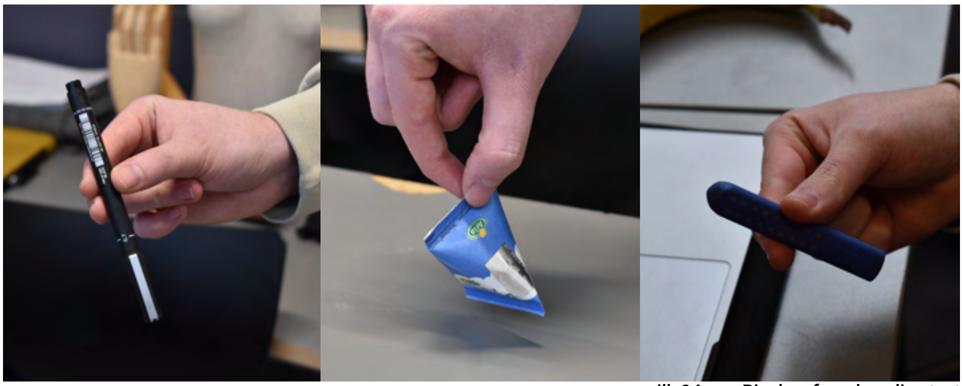


ill. 22. Hierarchy

The grasp
The grasp was used primarily when dealing with larger objects that required more power to hold onto. It is a gesture that utilises all five fingers to grip an object. The objects can be of varying sizes and the gesture can range from being completely tightened to almost open. This motion is also used in social interactions when near release such as handshakes and waving.

ill. 23. Grasps from baseline test

The pinch
The pinch is used to grab onto objects. Although this motion is primarily used for smaller objects. It therefore typically uses a three finger formation, tripod, with the thumb, pointer and middle finger or a two finger formation using the thumb and pointer finger.



ill. 24. Pinches from baseline test

The point
Unlike the other two gestures, the point is, by definition, not used to grip an object. During the test, it was used as an utility gesture to, as the name implies, point towards something. The finger when doing the point motion was usually not in contact with another object but rather used as a symbolic gesture. Only in the case of pressing a button and gently pushing small objects was this gesture used in a physical interaction.

ill. 25. Points from baseline test

c13: The product should enable the user to perform three hand gestures: the grasp, pinch and point.

Conclusion

Through observation, several motions used in daily activities have been mapped with the most crucial aspects related to the hand and being able to perform various hand gestures. After the hand, enabling elbow and wrist movement for the user increases functional application in daily scenarios. With these focus points in mind, the emphasis will be put on the hand, wrist and elbow moving forward, aiming to create a solution that enables the user to use these body parts to a sufficient degree.

Market positioning of exoskeletons

Introduction

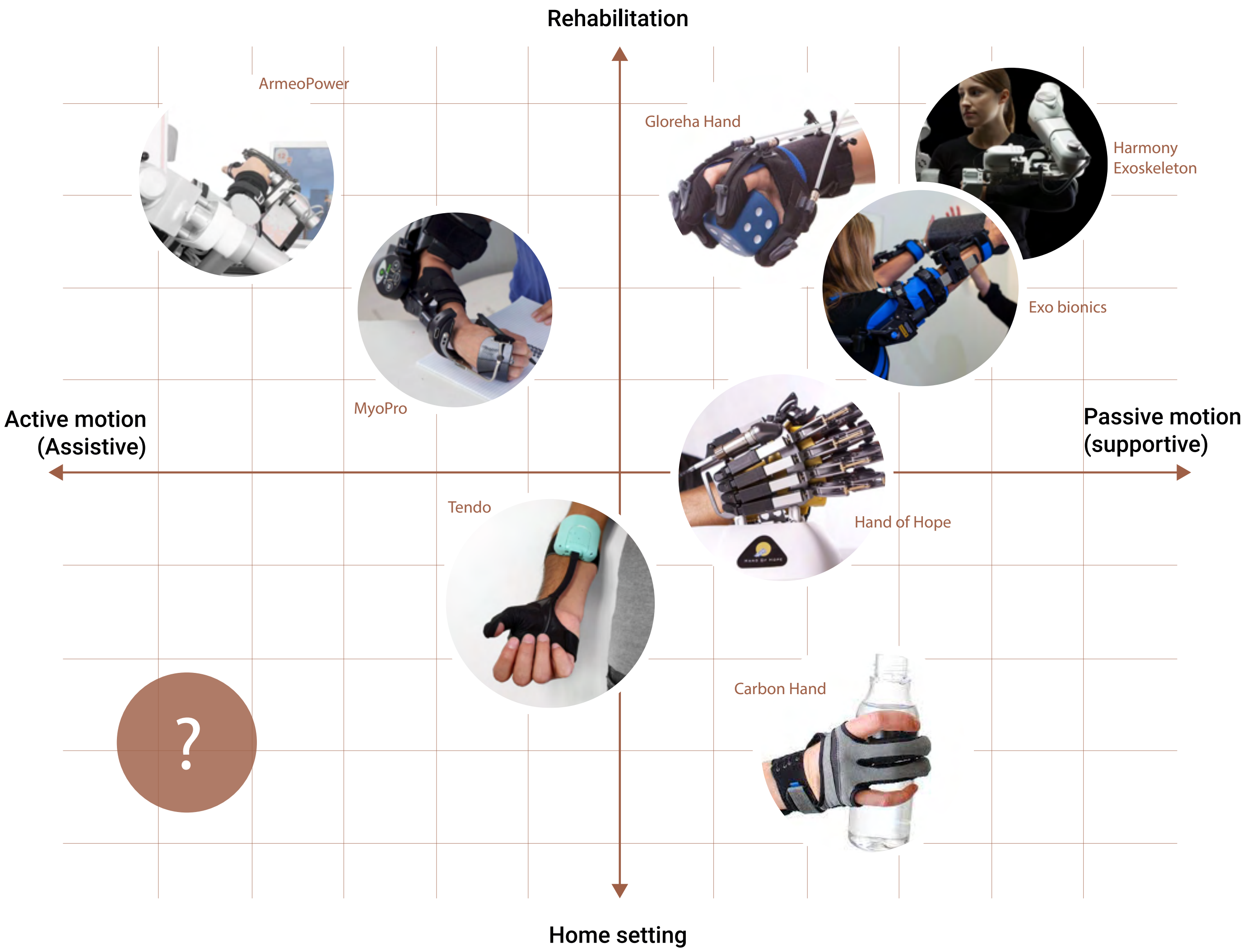
In order to scratch the surface of what the limitations are in the industry today and which particular problems exoskeleton adaptation is facing, different products and their prevalent barriers are researched. The gained information will be used to identify potentials and 'visualise' a common understanding and direction for the project. Furthermore, as the team had next to no knowledge of exoskeletons, these steps were a necessity at this point in the project, to make a qualified evaluation and product proposal direction.

For the making of this research several scientific articles, pilot studies and products currently on the market have been collected and read. Results and findings have been discussed and analysed in mind map brainstorm sessions (Tollestrup, 2004a) to align the knowledge and define relevant keywords.

Market positioning of exoskeletons

Different upper body exoskeletons on the market today have been mapped in the following model. The purpose was to identify how many products fit into rehabilitative and domestic environments respectively and provide the necessary strength to support the arm and hand fully.

It was evident that very few specimens found themselves in the lower left corner, which enabled full assistive active motion and are designed for a domestic setting. Most exoskeletons today are designed for rehabilitation purposes and reflect this both in terms of functions, aesthetics and adaptability. This leaves a gap in the domestic market segment.



ill. 26. Market position of existing solutions

Market gap for active exoskeletons for domestic-use.

Association analogy

Following the market positioning identification some of the products were explored further to describe which factors influenced their placement in the chart, and to align which associations they triggered. This was done through a variation of the metaphor-concept-metaphor (Tollestrup, 2004b) but with images as the point of reference. This led to the following key-takeaways regarding the perception of style and aesthetics.

ill. 27. Association analogies

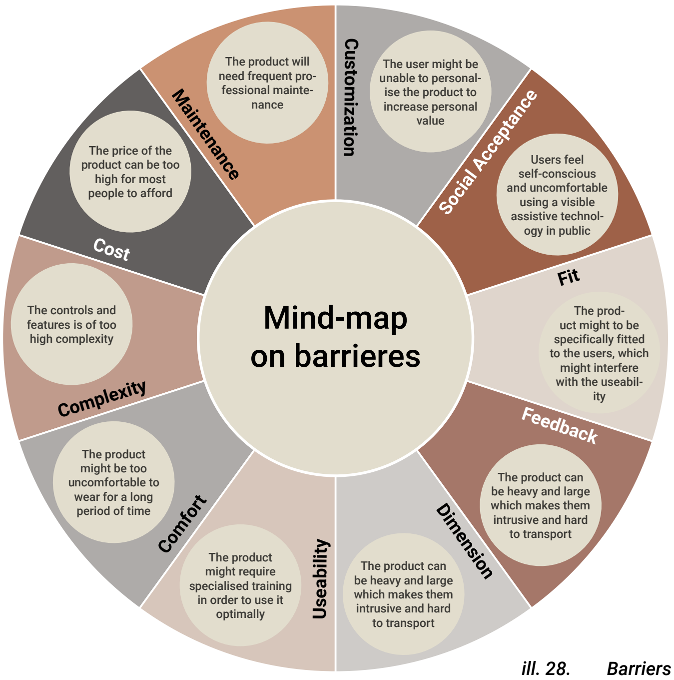
No current exoskeletons relate or associate to a "home-feeling".

The solution steps away from the mega-scale, clinical and aid-like image. And thereby help bring less attention to the user's handicap.

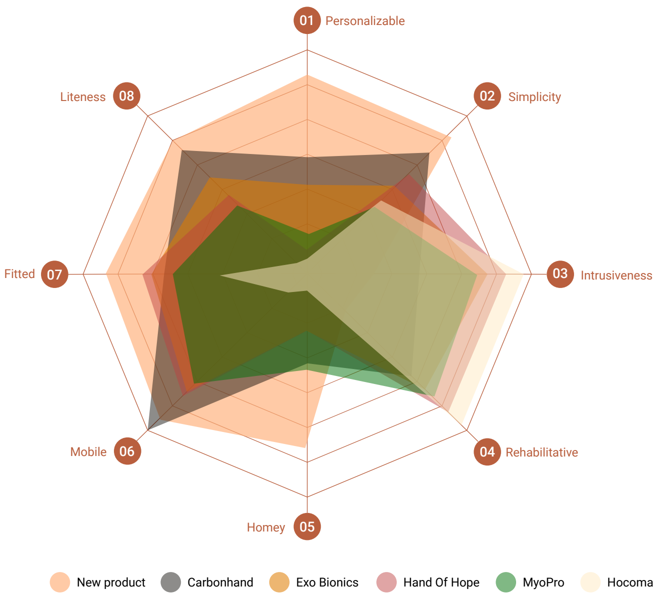
Brainstorm on barriers

The research and information collected from scientific papers and articles on exoskeletons were summarised into keywords following a brainstorm session. This in addition to insights from users and experts becomes keywords that describe identified barriers for successful implementation of exoskeleton products in an everyday setting. This was done to evaluate the barrieres and potentials within them.

Existing solutions were then evaluated based on these keywords in a spiderweb diagram to visualise the gap and posisbilities contra the market representatives now. The key words were based on a complement of themes from the prior research and user interview (pp. 14).



ill. 28. Barriers



ill. 29. Spider web diagram

The many design solutions on the market today clearly have a similar style and useability as evident from the chart. It bears the mark of having been designed initially for rehabilitation by mechanical engineers and stakeholders in the medical field, and is not intended for home-use.

"Upper-limb prostheses can be taken as an example where up to 75% of the users reject their prosthesis"
(Hernandez et al., 2021)

Conclusion

Lars and Hanne buy things that fit their identities and support how they would like to be perceived by others. The largest gap identified is how existing solutions do not resemble what people would wear; clothing, shoes, accessories, which is the norm, while neither allowing them to express their identity. The designs mostly associate to rehabilitative purposes and are not able to properly adapt to their context resulting in unwanted attention for the user. Ultimately, this misfit between products and context they seek to be used in makes it tremendously difficult to implement exoskeletons into everyday life. This reflection will be kept in mind in further development of the product proposal by differentiating from the existing form language.

Reflection: Blue ocean market potential

There have been identified a possible blue ocean market in regards to an customizable exoskeleton for the domestic setting. This proves well for the product proposal to aim to fill this gap to ensure a stronger market positioning, by bringing a new addition to the market and targeting a new and perhaps broader target group.

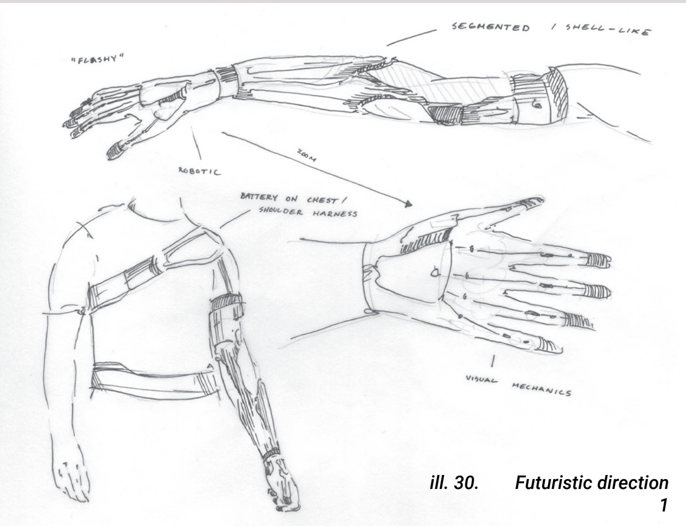
Concept development

Introduction

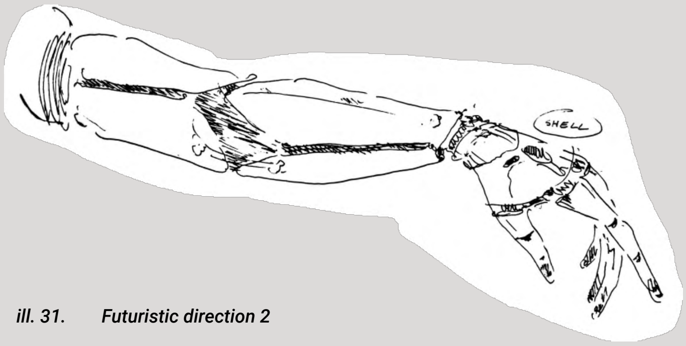
With an established base of knowledge regarding the level of mobility required and for the product solution and the user insights the team started ideating on different solutions spaces. The aim was to “kill our darlings” at this point, since the team has developed a favourite direction for the concept, and needed user feedback to discuss the potentials. The concepts below are a collection of ideation processes throughout the project up to this point and were now clustered (Tollestrup, 2004c) into three design categories: Futuristic, Clothlike and Customizable. These were evaluated against the findings from the user interview (pp. 14) and market analysis (pp. 21)

Direction 1: Futuristic accessory
Using the knowledge gathered from the user interview with Lars in particular, concepts were made that showcased the mechanical aspects of the product. The concept aims to showcase futuristic but sleek design language, where a rigid exoskeleton lays on top of the arm.

“If i should have an exoskeleton, then I would make sure people could see I was wearing one.”



ill. 30. Futuristic direction 1



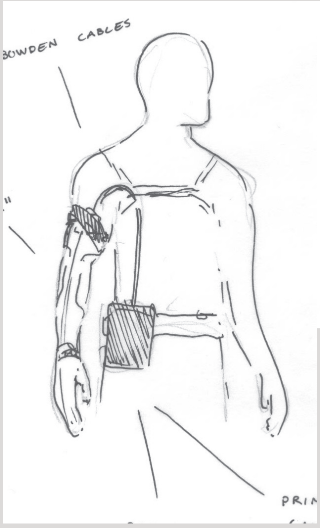
ill. 31. Futuristic direction 2

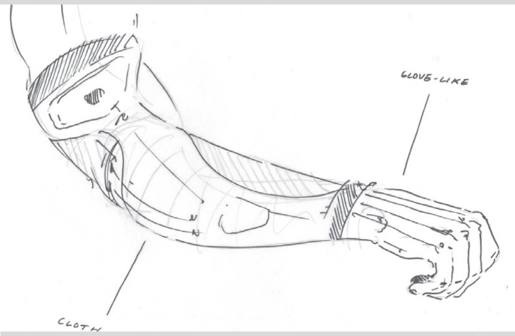
Pros	Cons
Futurism reflects function well. Interesting direction as a design push.	Too science fiction like. Preference may be gender dominant.

Direction 2: Clothing-like

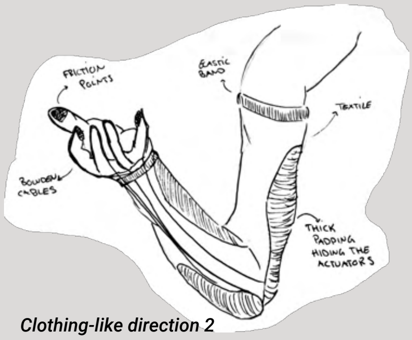
Aiming towards the polar opposite, using Hanne and one of the users from the user board meeting, other concepts aimed to fit a more anonymous style. These took inspiration from clothing and are constructed from soft materials which could easily blend into the user's daily outfits or be hidden under a shirt. To achieve a design this sleek, small cable actuators are used on the fingers and elbow.

"Yes it can look nice and such (...) But it should not take focus from me."





ill. 32. Clothing-like direction 1

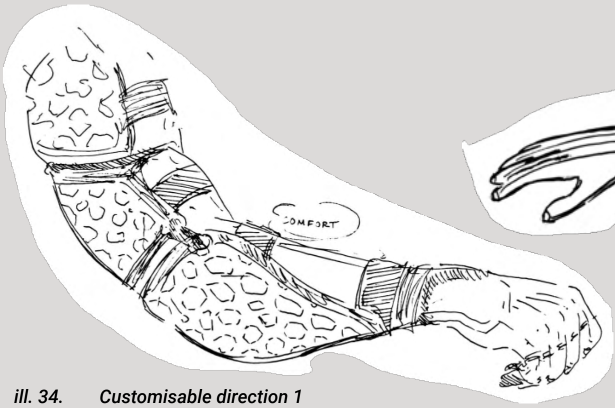


ill. 33. Clothing-like direction 2

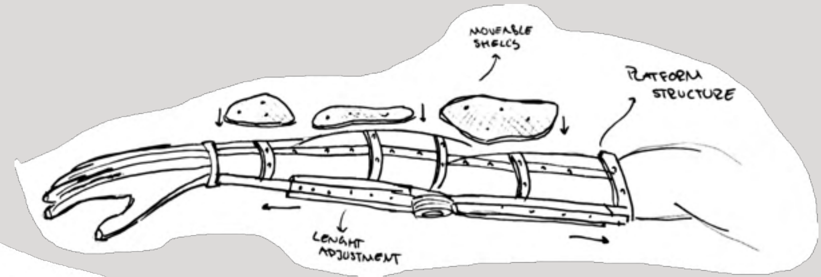
Pros	Cons
Can fit under clothes . **The disability is cloaked.** **Association to familiar materials and compositions.**	**Might compromise on function.**

Direction 3: Customizable

These concepts explored the possibility of adding a customizable element to the product to enhance the emotional value by enabling personification of the exoskeleton. They describe a modular product architecture, from which the users can interchange faces of the product depending on their preference. These concepts would require an inner structure for the mechanical components and a shell on top which could be detached.



ill. 34. Customisable direction 1

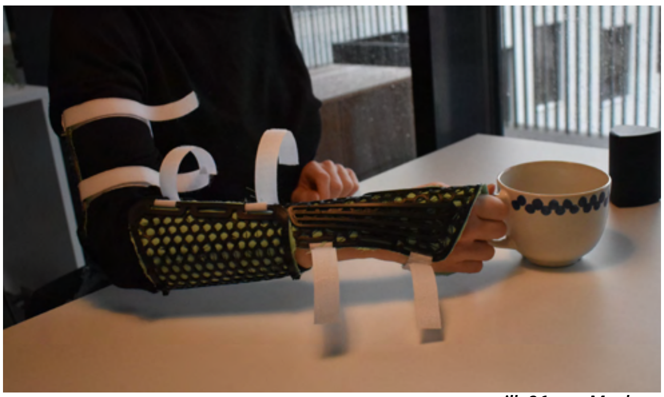


ill. 35. Customisable direction 2

Pros	Cons
Personification of the style. **Adjusting to the perfect fit.**	**Association to rehabilitative equipment.** **Rigid and mechanical look.**

Mock-up'ing of concept

One of the concepts from direction 3 was constructed in a mock-up to test out the form, fit and actuation idea early on. The mock-up was perceived too much as a brace for a rehabilitative purpose. The hole-pattern, placement and velcro lightening associated with hospitals and support for an injury. However the actuation principle consisting of manual caple actuation proved to work and stretched the arm by pulling the strings.



ill. 36. Mock-up

Conclusion

The team now needed to involve users and get feedback on the design directions and mock-up to move further in the process.

Feedback loop: Meeting 2 with Lars

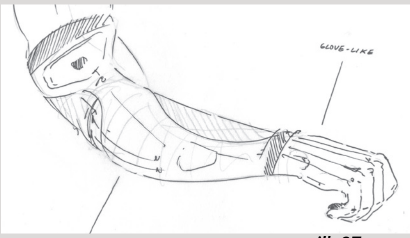
Introduction

To get feedback on the concept directions, and the projects as a whole, the thesis team chose to contact the users again. However, tight schedules and the geographic distance made it difficult, why only Lars found time for feedback. Given his competences in mechanical engineering, he could provide insights from an technical perspective as well while also keeping himself, as a user, in mind.

Feedback

The meeting was scheduled as a casual interview. It took place in Lars' study-room around a table, and was conducted with inputs from his group members to the questions asked during the discussion since they were also in the space. The team started by introducing the current status of the project and followed by the concept-ideas and directions, and from there a discussion emerged. (see apx. 13)

Clothing-like

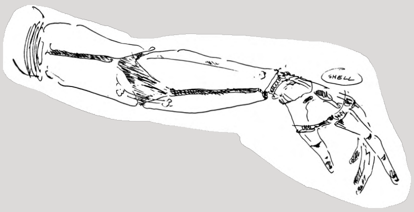


ill. 37.

Lars is concerned with the strength of the actuated textile and whether it would be strong enough.

He is resistant to the idea of active textile and the clothlike concepts as it would require pneumatic driven actuators. This would require a large compressor that causes a lot of noise each time the product is used.

Futuristic



ill. 38.

The product can not be too heavy as the user will easily be weighed down.

Mock-up

ill. 39.

Is sceptical of the working principle and if it could work in the real world.

Value proposition: Cost vs Function

One of the most relevant remarks was about considering the cost of the product when implementing more features. During the meeting, several points relevant to this area became apparent.

Tricep function
Lars did not like the idea of having the triceps included in the exoskeleton design since he does not use his triceps enough. Because of this, it would only add cost to the product without providing sufficient value for the users.

"I don't think it is that big of a problem, honestly. You can control a lot of triceps-enabled motions with the biceps. I'm using it as a counter force when my arm is extended by the use of gravity. It would just be in the way."

There was also a fear that it would become too bulky on the arm. The primary take-away from this conversation was that he desires the most essential features. Since his current level is next to nothing, anything would be better than what he currently can.

ill. 40. *Lars*

The cost vs function in implementing the tricep does not create enough value compared to the cost and physical bulk.

Ease of implementation
Another important aspect is how easily implemented the product is for the user. In this, specifically how much value the solution can provide compared to the alternatives. Lars has gone through different operations to regain some motion in his wrists and hands but they do not live up to his expectations causing a gap in quality.

He wishes for an easier and less invasive solution where he won't be hospitalised over long periods of time to regain only a small amount of movement back.

The users would like a solution that does not "take them out of commission" for longer periods.

c15: The solution needs to be easily implementable into the life routines.

"The thing with operations is that it is an invasive procedure, and I am hospitalised three months after, and won't be able to attend university. And then comes the rehabilitation process which can take years. You also don't know what result you are gonna end up with. So I refused any more operations at this time."

Conclusion

The feedback loop with Lars highlighted important features to consider for future development, and also made the team reevaluate their focus. It was evident that Lars had a hard time evaluating the concepts based on design since the basic functionality was not explored to the same extent, which created a lot of mistrust in the concepts. However the concepts with a clothlike look seemed most interesting to him and applicable for the use scenarios he invisions, but also sceptical whether it could provide the needed strength.

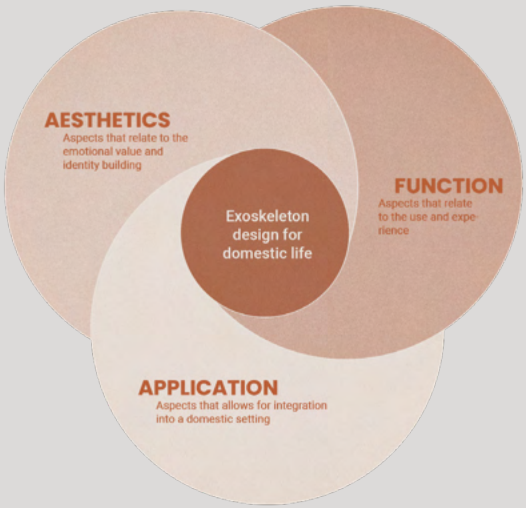
A main key-takeaway was the fact that Lars did not see any value in including the triceps actuation in the design. He saw the hand and fingers as the most vital part of the system, and would like to minimise the amount of equipment needed on a daily basis. This made the team stop up and reconsider the problem frame and specify to only work with the hand and how it could be adaptable to different identities.

Final framing: Exoskeleton glove

From this phase of the project, a final heading could be established for the design. Based on the user feedback and ideation process it is chosen to tighten the framing and work specifically with the hand by designing an Exoskeleton Glove.

Focus: the hand
The hand is the most vital part of any physical interaction with objects, and should therefore be the first focus when designing an exoskeleton for the arm. This leaves room for further development phases to implement additional parts of the arm in the future to enable full mobility of the arm. However as this is perceived as too big of a task at this point, the team will only focus on the hand, and based on this body part define the design direction for the product.

Clothing-like exoskeleton design: self-image
It was further decided that that product should aim to create a clothlike exoskeleton design. This design direction should push the industry to make products that more strongly considers emotional value, being able to adapt to their user's identity and support the way they want to express themselves in public. This concept-idea draws resemblance to the garments we wear daily and highly differentiate itself from the current market by reinterpreting what an exoskeleton can look like. The phenomenon of a fully functioning exoskeleton soft glove is not directly fathomable by the users, but sparks their interest the most.



ill. 41. Holistic model

Function
Providing the essential movement to function in an everyday context. Strong consideration to not implement feature creep and unnecessary features.

Application
The use outside of use. The product needs to fit into daily routines and rituals to ease the implementation into everyday life.

Aesthetics
A platform that enables the users to find a combination of elements that matches their self-image.

Design brief 1

Problem statement

How can the design of an exoskeleton-hand be optimised to fit into daily life by enabling tetraplegics to independently participate in social activities and provide a personalised experience that aligns with their individual identity?

Value proposition

An exoskeleton as personally tailored and essential your own spectacles.

Project overview

Major injuries such as SCI can result in tragic loss of motor function in various body parts, whereas for incomplete tetraplegics the loss of all function in the hands is a commonly seen result. This loss severity lowers their life quality, independence and ability to engage equally in activities alongside others. Mechanical exoskeletons have been a natural part of rehabilitation and training in recent years, but the market has not yet expanded properly to the domestic setting which enables the users to benefit from it privately. The few exoskeletons on the market today create undesirable associations to either science-fiction characters and workwear or disability and weakness which is prohibiting people from buying them. The language for the design is not yet uncovered, which leaves a gap on the market.

This thesis aims to design an exoskeleton glove proposal for domestic life, which will be marketed as a symbol of independence that reflects the user's self image. This will be done by helping reduce the social barriers of adopting exoskeletons into daily life by making wearing and using an exoskeleton equivalent to wearing and using shoes everyday. This way the project aims to make a concept proposal which will demystify living with wearable robotics.

Target group

The target group is incomplete tetraplegics with no function in their hands. This group is based on the recruited interviewees and user base available, as their injury makes them an ideal target for the product proposal. However, even though they are not necessarily the only main user for the product proposal on the market, they will stand as the user case-example in this thesis.

Business potential case

There is identified a possible large market and scaling potential for this proposal. Injuries like stroke, ALS, traumatic injuries or nerve damage can cause loss of function in the hands. This opens up the market remarkably and validates that designing a modular product architecture and platform could enable customization for each user group. The design process will therefore take this into account during the development and will be explored further later in the thesis report.

Project Criteria

The initially found criteria for the product has been collected and ranked below from most vita criteria to explore for the solution, to basic criteria expected in the solution. All requirements are now unspecified and still have an open solution space. The requirements will be used throughout the development processes and guides and be specified further as the project progresses and the team regains more knowledge.

Design dilemmas

The exoskeleton arm should be a personal extension for its user BUT not something they are defined by.
It should could be a conversation starter BUT not remind them of their disability.
It should assist the user WITHOUT it being intimidating.

c10: The product should be fitted an individual user identity

c3: The design must be fitted for the home-scenario

c11: The user should fully control the movement

c12: The solution should be aesthetically customizable

c9: The design should dissociate from hospital/rehabilitation equipment

c14: The product should enable the user to perform three hand gestures: the grasp, pinch and point.

c15: The solution needs to be easily implementable into the life routines

c8: Should be able to be worn under a jacket.

c4: Should not be removed too often in a day.

c5: Should be fitted to and account for the wheelchair.

c13: The product can not hinder the user's existing movement capabilities.

c2: The solution should provide higher independency

c1: The solution should be applicable across different genders and age

c7: Should take up minimum space.

c6: Should be lightweight.

Function

Phase 3

This phase navigates the functional perspective of the holistic model. It focuses on exploring, understanding and deciding mechanical principles to achieve the desired user experience, and enabling function in the hand. Through problem slicing and mock-ups, different aspects of the product are researched and tested to create a solution that fits the vision of seamless implementation into everyday life. All this culminates in a design brief showcasing the identified insights, requirements and dilemmas, as well as a reflection on the process of matching principle choices to the vision.

Experience benchmark

Introduction

One of the identified barriers in current exoskeleton products is that the movement is often very mechanical. The users do want to appear and feel more disabled than they currently are (criteria c9, pp. 14), and therefore the thesis team deems it rational to work towards a product that mimics how a well-functioning hand operates and feels.

As is scenario

From the second visit with Lars, he was observed doing basic iADLs before the team, so the current to assess his movement patterns and work-arounds when trying to grab an item without assistive tools. These mappings and videos were used as a point of reference to the user mobility throughout this phase, since the team had a difficult time mimicking the users movability restriction in the upcoming tests.

A loss of control
Lars' hand is completely immobilised and the grip he had on the bottle is supported by a combination of low weight, balance and support of the other hand. But as soon as he tried to drink, gravity made him drop it. This strugglesome display can make the individual self conscious and can bring unwanted attention in a public space.

Natural flexibility of the hand
The natural resting position of the hand is here used to get a grip around the object. Naturally the finger flex slightly inward which makes it possible to get a seamless grasp on the bottle to make it easier. A reflection from this is that a semi-closed hand might be difficult to wrap around a cylinder without the hands needing to be extended actively beforehand, but this would require an extra action from the user to call "open" and then "close".

1. Pushing hand against bottle | **2. Forcibly opening the hand using the bottle** | **3. Re-adjusting grip** | **4. Supporting with the other hand** | **5. Lifting the bottle to mouth but dropping it instantly**

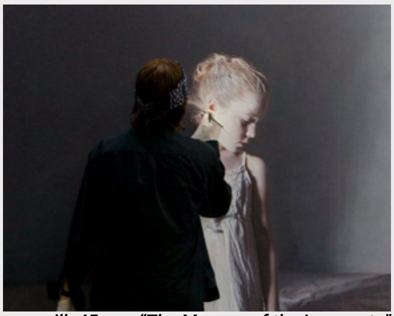
ill. 44. As-is example

Benchmark metaphors

The product will never be natural in the sense that it is not part of the user's body. However, it should be designed to mimic natural movement to a sufficient degree where the user and their surroundings does not recognise they are using an assistive device. To achieve the desired user experience, metaphors are set up that describe how it should feel and be perceived when in use. This was done to, internally in the team, align the common understanding of the experience vision by visualising it.

Lifelike

The product should feel as lifelike as a realistic painting, only revealing the brushstrokes in the solid colours when examined up close.



ill. 45. "The Murmur of the Innocents"

Agile

The product should be as agile as a ballet dancer gracefully moving through their routine in quick, dexterous and smooth motions.

ill. 42. Ballet dancer

Controlled

The product should be as controlled as a marionette moving exactly as the master puppeteer wills.

ill. 43. Puppet master

Gesture experience

Introduction

Having identified which movements the product should enable for the user, different options are now investigated to determine which gestures are most suitable for the product. The process of finding the options is heavily based on counter measuring some of the identified barriers and achieving the Experience Benchmark (p. 29).

Actuation Principles

Different actuation principles are explored to diverge the solution space even further with the intention to diverge it down to one focus principle (see apx. 19). Based on a grand research of exoskeletons and prosthesis, it was noticed that different actuation principles have differing movement patterns relating to a visual appearance. As the team was not able to test any other princplæes, besides the EXOTIC, videos of prototypes and hobby projects helped assess the perceived experience. To determine which principles to dive into, they were each assessed in a morphological analysis against the Benchmark Metaphors. When evaluating the actuation principles, the capability for natural-like movement and how compact and/or easily hidden the technology is, are heavily weighted parameters. Especially two principles caught the team's attention

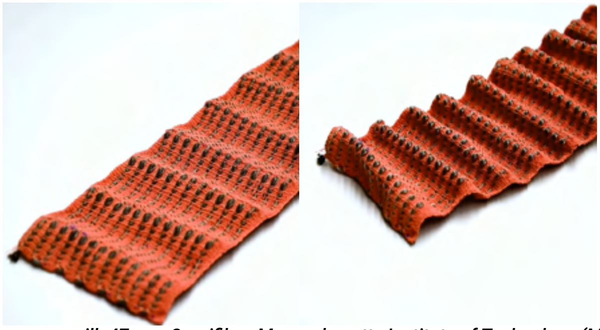
ill. 46. An exoskeleton glove with a very visible mechanical principle

Disregarded: Active textile

Active textile is a rather new technology that combines electronic components interwoven with textile. Visually, it just looks like textile but with added mechanical properties either through electronic or pneumatic tubing. Unfortunately, there is a severe lack of available information on it or proof-of-concepts, with only a few use cases with smaller patches of fabric that are able to twitch or contract. And because of this, the option alone is disregarded.

However, the seamless integration of mechanical components woven into fabric, was very inspiring to the team and was in sync with the desired vision. The visual expression of the actuation principle was deemed neutral and familiar with a highly agile movement pattern.

A clothing-like appearance makes the product easier to blend into the user's outfit.



ill. 47. Omnifiber, Massachusetts Institute of Technology (MIT)

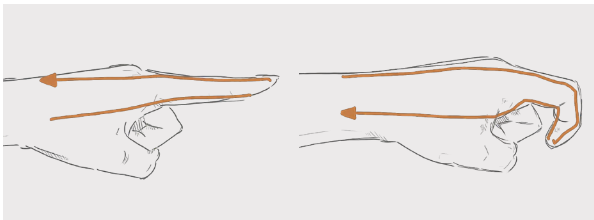
Chosen: Tendon actuator

Tendon actuators are a quite established, yet evolving, technology that exists in several relevant use cases in various products. As the name suggests, the mechanism consists of cables that act as tendons mounted on the tip of the finger and pulled to flex the finger towards the palm or vice versa.

There are several reasons why this principle was chosen but the two most prevalent are that tendon actuators mimic human anatomy to a particularly high degree. Secondly, the mechanism can be made fairly compact, allowing for a wide array of possible design directions as the cables require little space. These align very well with the identified requirement of an lifelike movement and a small mechanism to lessen the visually robotic appearance.

The product uses tendon actuators as its mechanical principle.

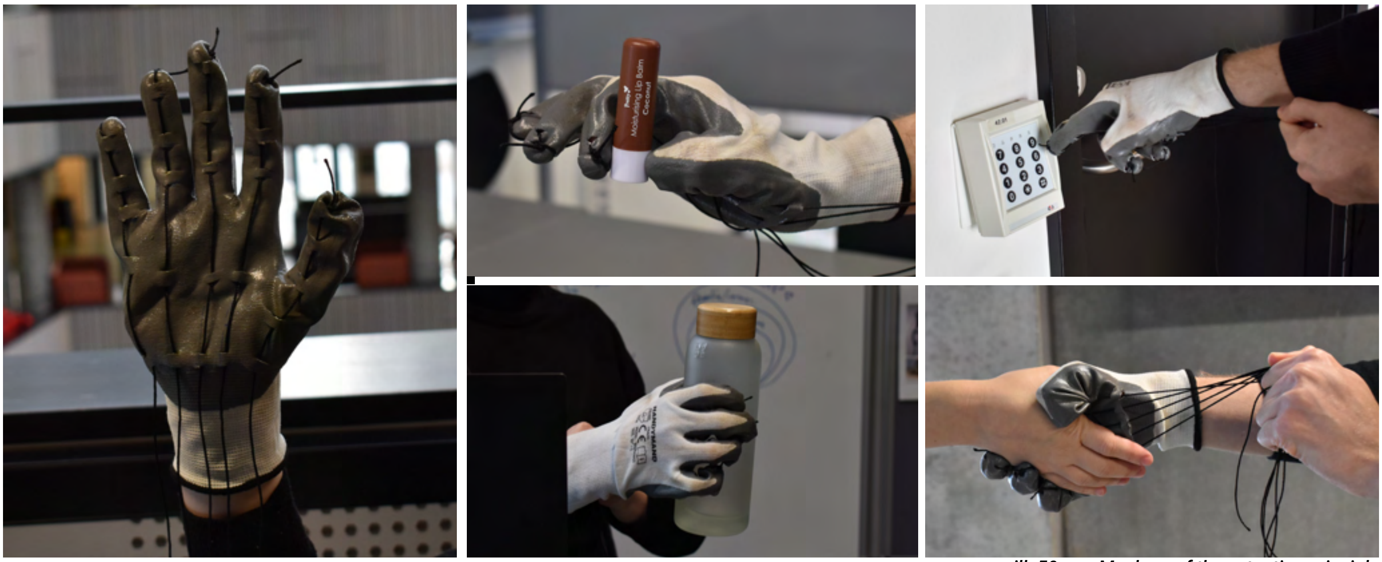
ill. 48. Prototype of tendon-based exo-glove



ill. 49. Tendon principle

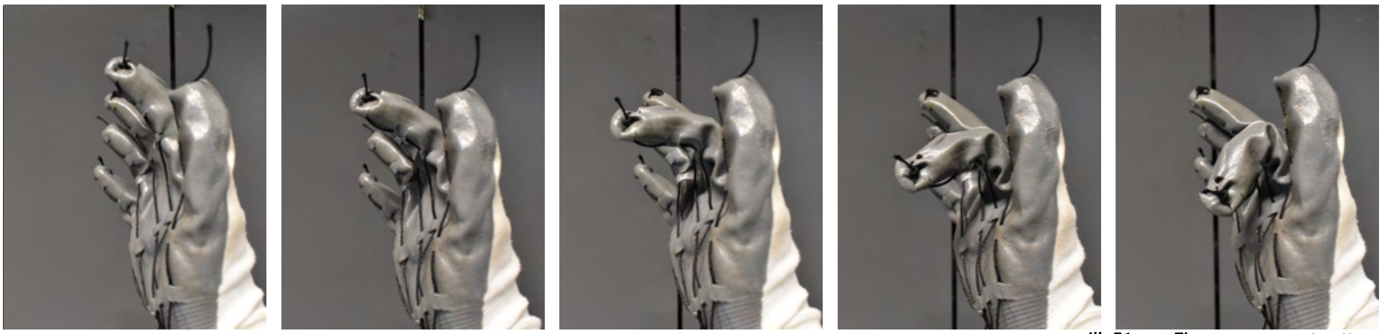
Mock-up of cable actuation principle

With the tendon actuator chosen, the thesis team decided to make a quick mock-up to test the mechanical principle on themselves and colleagues. The purpose of this was to test the experience of the movement and external actuation. For the tests a mock-up was made with a simple one-string artificial tendon (bricklayer's cord) mounted through the holes of a glove. The tests are based on testing the three identified hand gestures: grasp, pinch and point, and relevant iADL scenarios (pp. 19).



ill. 50. Mock-up of the actuation principle

Despite functioning to a certain degree, the fingers closed in an unnatural way where the joints bent in a sequential manner; first the DIP, then the PIP and lastly the MCP. This resulted in an overall unfavourable finger position when attempting the grasp or pinch. Visually it also looked rather odd.



ill. 51. Finger movement pattern

Conclusion

The thesis team has chosen tendon actuators as the mechanical principle for the product because it at a glance fits the experience vision and tackles some of the identified barriers. However, after testing it using a crude mock-up, it was discovered that it did not make the fingers move as desired. Moving forward, the placement and routing of the cables needs to be explored further to provide the "correct" finger closing pattern.

Reflection: Test validity

It was also quite difficult to imitate a tetraplegic with no finger strength without limping the wrist. By limping the wrist, it made it difficult to test the identified gestures properly. This added a big source of error in the testing that needs to be addressed in another test.

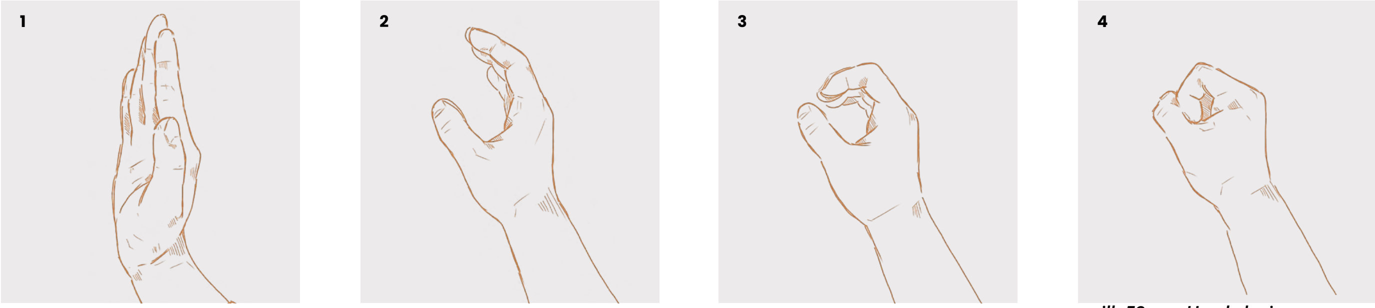
Problem slicing: Active and passive

Introduction

The next step was to explore the extension and flexion of the hand with the tendon actuation principle. There is a time when the user will use the product actively and other times where it will simply be on the hand. Both scenarios were explored through a problem slicing process, where each principle was tested via mock-ups. When the product is in use, the entire hand will transition between different positions. One of the parameters of the experience benchmark is that the product should appear lifelike. A part of achieving this vision is to ensure the hand does not move in an unnatural way and is in a natural-ready position when out of use.

Defining a natural closing motion

When testing the cable actuation principle mock-up, it was discovered that the hand closed in an odd way that functionally and visually was not desired. The most natural closing mechanism involves all joints bending almost simultaneously rather than in a sequential manner where the DIP bends first, then the PIP and lastly the MCP (see ill. 52).



ill. 52. Hand closing sequence

The DIP, PIP and MCP joints should bend approximately simultaneously.

Defining a natural resting position

Looking at the hand of a well-functioning individual, the natural resting position is not with the fingers completely stretched out but rather slightly bent. In this position, the fingers form a hollow shape at the palm. This not only looks significantly more natural than a fully extended straight hand but also serves a functional purpose in making it easier to perform grasping and pinching motions. For this reason, the resting position can not be too closed as well.

ill. 53. Resting positions

Passive resting position of 20 degrees.

Conclusion

By taking a step back and looking at the product's function in a very simplified way, it is evident that the product can inhabit two states: an active state in which the fingers move and a passive state where the hand is in a resting position. To fulfil the experience vision, both of these need to look as natural as possible. Moving forward, the active and the passive aspects should be explored further.

Disclaimer: Parallel process

During the design process, large parts of the following development happen simultaneously with parts of the solution iterating a number of times. For the sake of presenting the process in a more easily understandable manner, the development in this phase will be split into two parts: Active flexion and Passive extension.

Active flexion 1: Flexion of fingers

Introduction

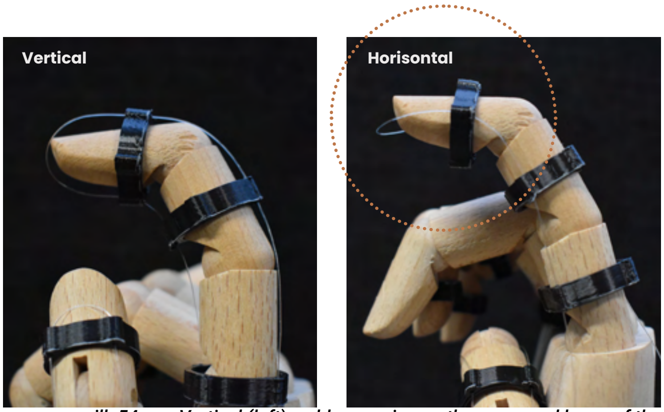
It is crucial that the cables enable a natural movement in which all joints of the finger move synchronously. It is now explored how and where the cables should be placed and in which configurations to achieve the desired motion is unfolded.

Mock-up: Rings to test cable placement

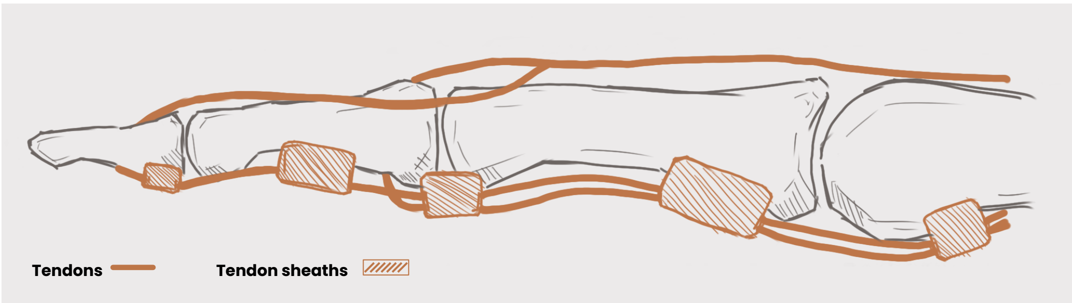
To test the placement of the cables, several rings with holes were 3D printed. These rings could be rotated to test different placements of the cables. The holes fulfil the same role as cable sheaths to guide the wire along the finger. From the research on the hand, the rings should be placed near each finger joint: the DIP, PIP and MCP. For the cables, 0.3 mm nylon wire is used.

The two directions provided a similar motion. The vertical direction was slightly stiff and inclined to get stuck, whereas the horizontal direction produced a smoother movement. For this reason, the horizontal direction is chosen.

The cable placement was also supported by research on the hand structure in which the natural flexor tendons run along the sides on the lower part of the fingers. The horizontal positioning would therefore be explored further into depth.



ill. 54. Vertical (left): cables running on the upper and lower of the finger, and horisontal (right): cables running on the sides of the finger

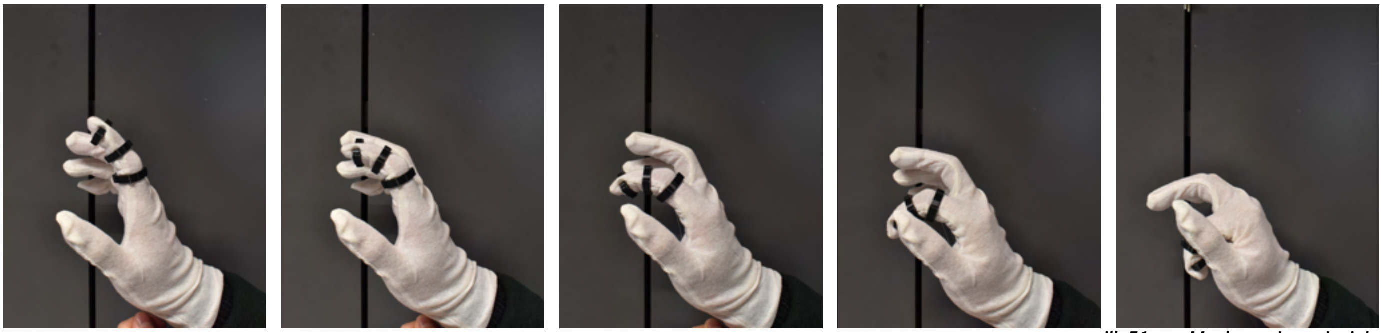


ill. 55. Natural tendon placement

Mock-up: Ring-principle on glove

The previous test conducted on a wooden hand, was furthermore should be tested on a human hand as well to test the experience motion. The rings are put on a gloved hand in the same manner as the previous test.

The hand was still closing but had a tendency to put most of the pulling-pressure on the outermost joint, the DIP, which resulted in a sequential motion. This may be due to a major source of error in regard to the fit and elasticity of the glove. The thesis team noted that it was difficult to evaluate which tendon placement actually had an impact on the movement. Therefore, more tests were planned where different placements of the sheaths could be explored in a more controlled environment.



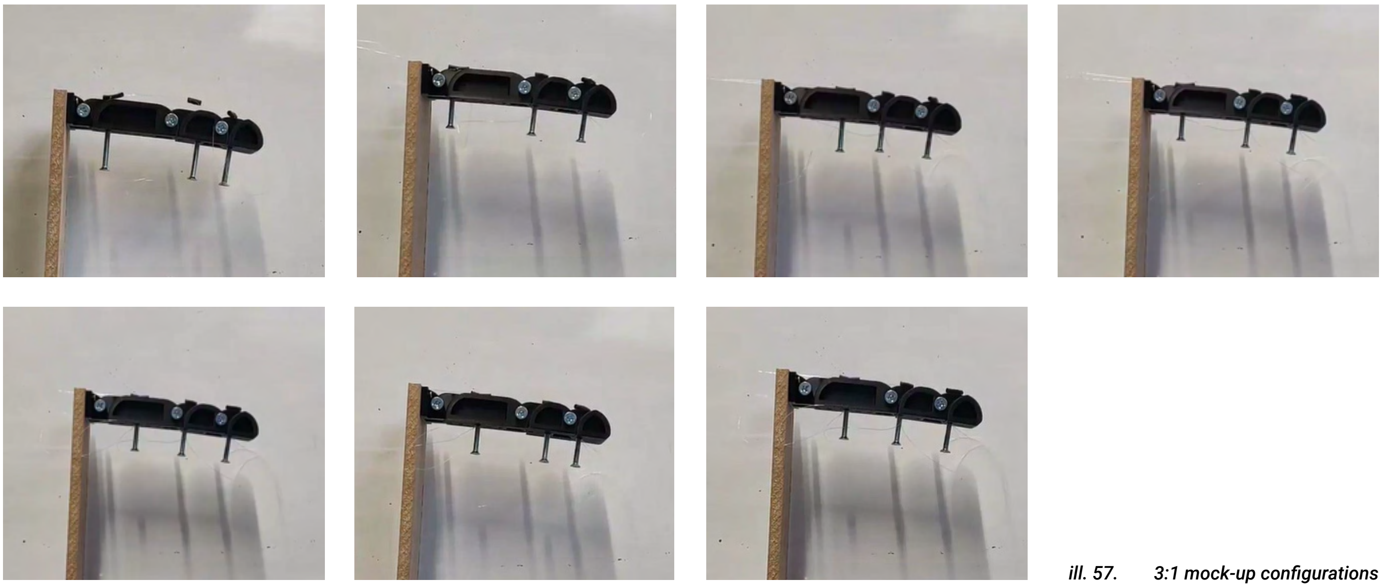
ill. 56. Mock-up: ring-principle

Mock-up: 3:1 finger model

To reduce as many sources of errors as possible, a test setup was built of a 3:1 scaled finger which made it easy to spot the movement sequence. The finger was up-scaled based on a team member's finger, and afterwards 3D printed and assembled with screws. (see apx. 17)

The setup
The test was conducted by mounting the 3:1 finger on a wooden stand, and setting up a camera to measure the precise movement sequence of the finger when actuated by the tendon.

Seven different cable configurations were tested in the setup with differing sheaths positionings around the joints. The hypothesis was that differentiating the anchor point would affect the order of which joint flexed first.



ill. 57. 3:1 mock-up configurations

Results
Unfortunately, all tests showed the same results, where each joint flexed one by one insead of simultaneously. The conclusion was that the test setup had too many sources of error; the tendon string (bing fishing cord) was too flexible, too high friction and the joints were too loose. Furthermore the finger was in a constant hyper-extended position, which did not simulate the natural flexibility of a finger. This was a minor setback for the team, which prompted work on defining the passive extended position next, in the hope that the knowledge could be implemented to improve the test setup.

Conclusion

To enable a natural closing motion of the finger, the joints should bend nearly simultaneously. The tests of principle mock-ups have proved that placing the tendons along the sides on the palm side of the hand mimics human anatomy the best. However, after testing it on test subjects, it became evident that the uncontrollable parameters such as, the natural urge to flex and unfitting glove sizes, hindered the team in getting any closer to understanding the ideal cable placement and routing. A more controlled and systematic approach was taken with 3:1 finger mock-up, which unfortunately did not bring the desired results. Because of this minor setback the team continued the development but on another problem being the passive extended position of the hand when not in use.

Reflection: Height in relation to the joint

It was discussed and tested whether the height in relation to finger joints could also impact the motion. After testing several iterations, it was concluded that there was too great a distance even when keeping the cables as close to the finger as possible to observe a noticeable change. Because of this, the thesis team decided that the best course of action would be to just keep the cables as close to the finger as possible.

Tendon sheaths are placed as close to the finger as possible.

Passive Extension: Hand resting position and brace

Introduction

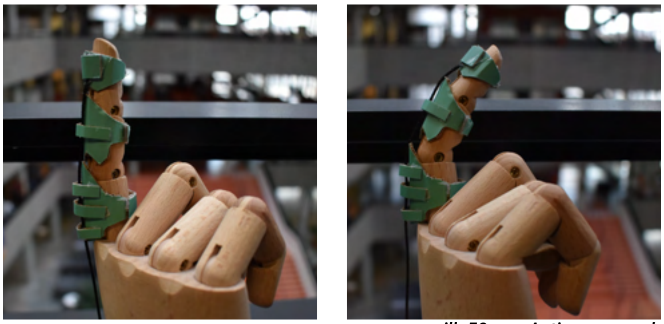
This chapter explores two significant aspects relevant for the passive extension of the product. Firstly, the hand should be able to return to the identified natural resting position after use. Secondly, it is relevant to address the previously identified difficulties during testing: the limping of the wrist, and make the hand gestures easier to perform from the resting position.

Achieving a natural resting position

To make the fingers return to the desired resting position, the thesis team saw two possibilities.

- Incorporating tendon actuators on the back of the hand.
- A passive method of actuation that makes the fingers jump back to start position.

A quick mock-up was made with tendons on the upper of the finger to test option 1, and elastics for option 2. However, after short deliberation, it was chosen to pursue a passive actuation approach (option 2) to avoid implementing more actuators and motors, which increases price and complicates the system unnecessarily.



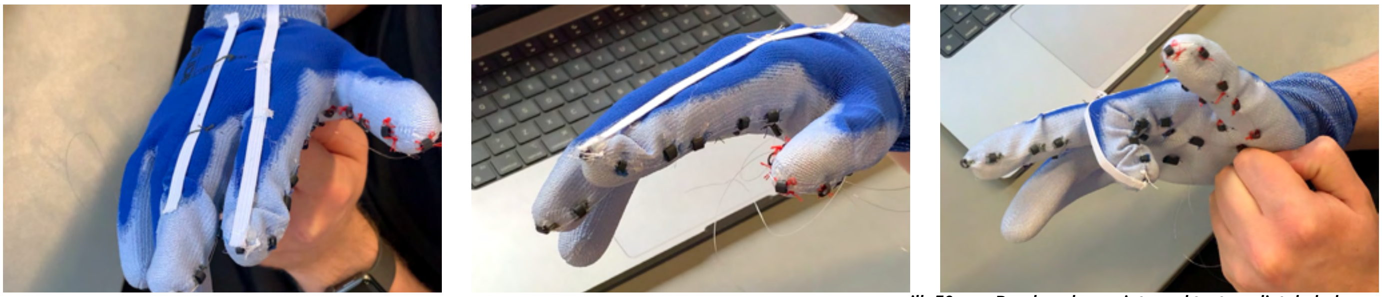
ill. 58. Active approach

Passive extension via elastics

Given the focus on sleekness in the design and small volume (criteria c6, c7 and c8), and taking a clothing-like approach, it was chosen to use a strong type of woven elastic bands as the passive actuation for the following tests. These types of bands come in a variety of widths, and do not overstretch nor lose their shape (Kiron, 2021).

Woven elastic bands were sewn to a glove to imitate the passive actuation feature. The band was sewn to two different anchor spots to test the placement. The first being at the tip of the distal phalange and the second being near the DIP joint. The other end of the band was anchored near the knuckle while being stretched enough to pull the finger into the desired resting position.

Distal phalange



ill. 59. Band anchor points and test on distal phalange

DIP joint

ill. 60. Test on dip joint

After testing on subjects, the preferred design was the mounting on the DIP joint. The placement on the distal phalange pulled the glove backwards and felt uncomfortable on the joint. However placement on the DIP joint felt natural and the compression force of the elastic could not be felt, which is why this anchor point was chosen as principle.

c20: Uses elastic elements to provide passive opening.

c21: Woven elastic are anchored at the DIP joint and edge of the wrist.

The wrist and thumb

A recurring problem during tests is the problem of imitating the user group. The test subjects have attempted to act out the role of incomplete tetraplegics meaning they need to completely relax their fingers. At the same time, they could not limp their wrist as it would make the tests severely difficult to conduct when pulling the cables.

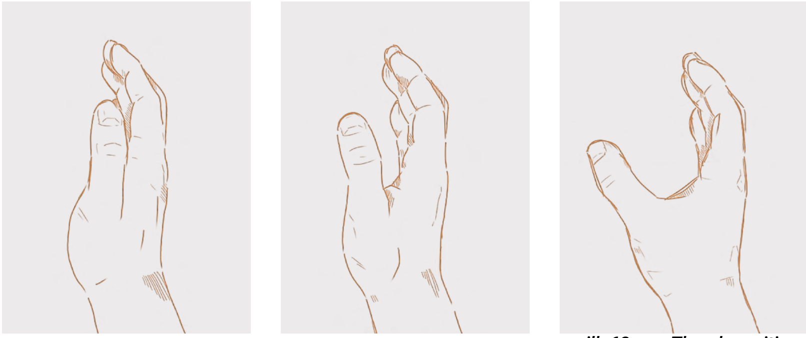
Looking at the user group, they are unable to move these muscles altogether making the wrist go limp. They also can not put the thumb in an advantageous position but need to position the hand around an object.

ill. 61. Lars' brace and wrist

Simplifying the product
To combat the risk of device abandonment, the product is kept as simple as possible. It is therefore decided to not delve into implementing technology that can actuate the wrist and all of the thumb at this point. Insead a concept of locking the wrist in a fixed position is explored. This is inspired by the wrist bands Lars and Hanne are using currently to fix their wrist when using the wheelchair. A potential to solve more potential problems with one solution was discovered.

The brace

The functional principle of introducing a brace to keep the wrist fixed was tested. A simple brace was sourced online, to be 3d printed and shaped after the hand by heating it. Besides only locking the wrist, an idea sprung to form the brace further to fix the thumb in a position that allows the user to perform the hand gestures. It was identified that the thumb must be in a semi-abducted position of about 89 degrees to be able to do so. Looking back at the baseline test, it was observed that the subjects shaped their hand in a C-shape when performing the gripping gestures.



ill. 62. Thumb positions

The setup
The brace was attached to the hand using velcro straps. The rings and tendons were also attached acting as the tendons. A quick test was conducted where the three gestures are performed. It was observed during the test that incorporating a brace into the product solves several of the encountered problems. However, it is noted that the brace is very uncomfortable to wear when it does not perfectly fit the hand. Regarding the brace design itself, the thumb should be slightly more abducted than constructed in the mock-up, which will bring it closer to the 80 degrees.

c22: Locks the thumb in an 80 degree abducted position

ill. 63. Mock-up test with brace

Conclusion

Woven elastic bands are implemented into the product to provide passive actuation and return the hand to a natural resting position after use. This choice was made to reduce electrical components and effectively reduce the size requirements to the battery. In addition, a brace is also implemented to fix the wrist and lock the thumb in an 80+ degree abduction position, which makes it easy to perform the gestures. Combined the two leaves the hand in a resting position which is gesture-ready and does not seem og feel uncomfortable.

Reflection: Height in relation to the joint

In regards to the vision of reducing the association to disability and weakness, the addition of a brace might conflict. The brace used in the mock-up is designed for injury, as braces typically are, and by introducing it the team might risk not working towards the set value vision. Because of this the brace design would be explored further aesthetically to make sure it could provide additional value and function to the user.

Active Flexion 2: Cable Routing

Introduction

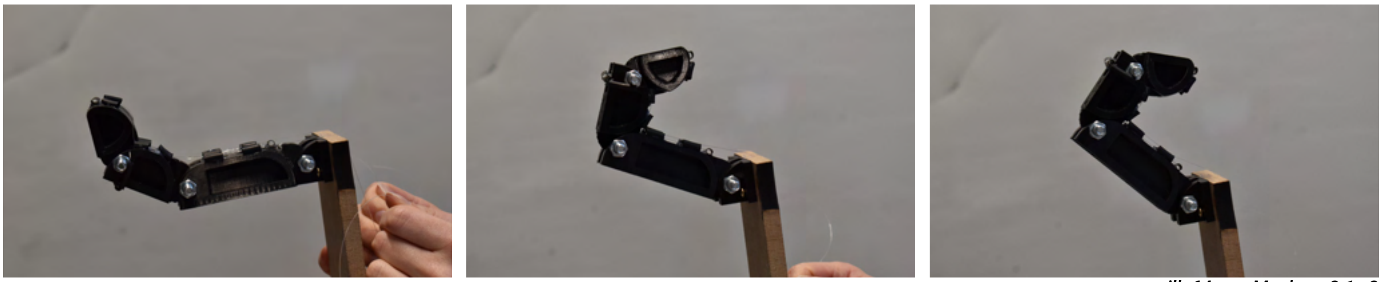
With the passive extension principle defined the team returned to the cable routing tests to define the ideal route. An additional visit to REROB and meeting with Mostafa was conducted to get expert feedback on the issues the team was facing. This was followed by additional tests of the 3:1 mock-up with the new knowledge implemented.

Mock-up: 3:1 finger model v2

A meeting was planned with Mostafa to discuss the status of the project and get insights into what could be improved from an robotic engineering perspective (see apx. 14). Overall, he was happy that the thesis team had decided to pursue another direction than intentionally, and that the findings might be valuable to their projects as well. The discussion primarily revolved around the cable routing, and the team was advised to seek inspiration from the direct anatomy of the finger.

For this test the team took Mostafa's advice and based the routing on the physiology of a finger and placed the sheaths accordingly, with the specific routing set up inspired by research by M. Abdelhafiz (Abdelhafiz, M.H. et al., 2023). Additionally the passive extension technique of implementing elastics was added as well, bending the finger slightly in the desired position. To eliminate the sources of error from the last test, the anchor points were set as close to the joints as possible, and the tendon was switched for a thicker 0,7 mm one with less elasticity. It should be noted that there was still a significant amount of friction between nylon wire and anchor tubes

The test provided the desired results with the finger bending in the natural sequence smoothly. This configuration was therefore implemented in a glove to test the user experience. (see apx. 21)



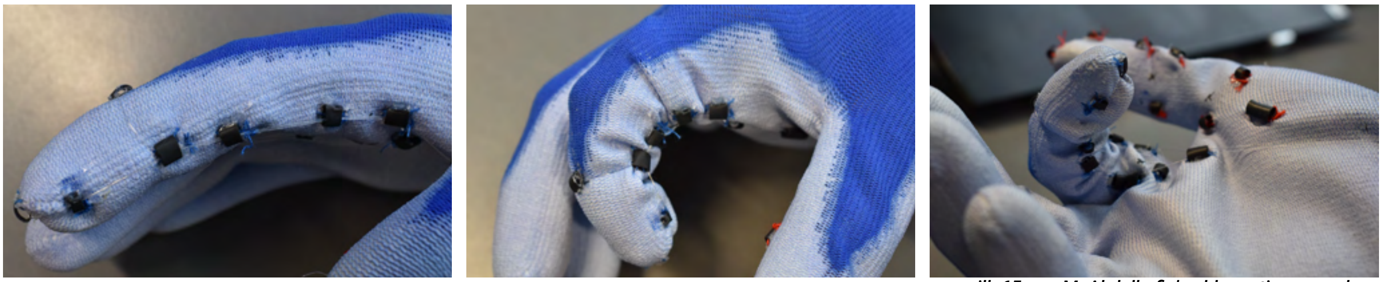
ill. 64. Mock-up 3:1 v2

Mock-up testing: Found cable route

For this test the team took Mostafa's advice and based the routing on the physiology of a finger and placed the sheaths accordingly, with the specific routing set up inspired by research by M. Abdelhafiz (Abdelhafiz, M.H. et al., 2023). Additionally the passive extension technique of implementing elastics was added as well, bending the finger slightly in the desired position. To eliminate the sources of error from the last test, the anchor points were set as close to the joints as possible, and the tendon was switched for a thicker 0,7 mm one with less elasticity. It should be noted that there was still a significant amount of friction between nylon wire and anchor tubes

The test provided the desired results with the finger bending in the natural sequence smoothly. This configuration was therefore implemented in a glove to test the user experience.

M. Abdelhafiz' version



ill. 65. M. Abdelhafiz' cable routing on a glove

After testing the glove internally and on four other individuals, the routing would produce an adequate movement pattern and provide sufficient grip for small objects. There was a possible source of error on the configuration. When looping over the finger and when the wire ran twice through the sheaths, it would get slightly stuck due to the friction.

Therefore a simplified version was tested with a similar design as the first, which showed very similar results. Considering production and manufacturing, the simplified version is thought to be the best option, possibly lowering the manufacturing cost while still providing the same lifelike flexion sequence. Therefore, this cable configuration is chosen.

Simplified version

ill. 66. Simplified cable routing

c23: Tendon sheaths run on the sides of the lower half of the finger.

c24: The material needs to be slightly stiffer where the tendon sheaths are placed.

Conclusion

After iterating on different cable configurations, a solution that achieves the desired motion has been identified. Tendon sheaths are placed as close to the fingers as possible in the 'simplified' configuration. The cable runs along the sides of the finger and to the distal phalange, connecting at the base of the finger at the carpo-metacarpal. This configuration provided a likelike flexion sequence and natural experience, while still accounting for lowering manufacturing costs and assembly time.

Closing speed

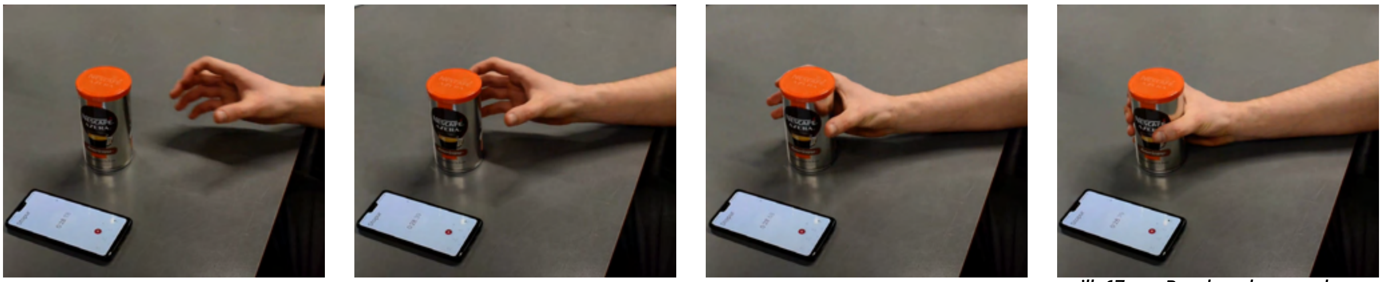
Introduction

The speed at which the finger completes the motion is crucial to get an agile and lifelike experience. The closure being too slow can inevitably cause boredom or make the movement seem too artificial, whereas a too fast motion could shock and feel un-controlled. Both scenarios could lead to product abandonment, and clash with the initial function-vision of the project. Therefore, a speed that visually and in-use feel appropriate is investigated in different ways. A test of the functional mock-up attached to a machine drill is executed on test subjects, who would provide feedback and rate the different speeds. (see apx. 23) Additional research papers on the speed of prosthesis were collected as a base for comparison.

Benchmark: Natural manual grasp

Throughout the movement, the speed of the hand varies slightly. The first phase of the grasping, in which the hand is nearing the wanted object, the speed is significantly slower than when near the object and ready to close. Ultimately, after identifying grasping speeds, the grasping motion was closer to 0.5 s. This benchmark test was conducted as a baseline for the natural motion and which speed the team should expect to strive towards.

Approximately 0,5 seconds →



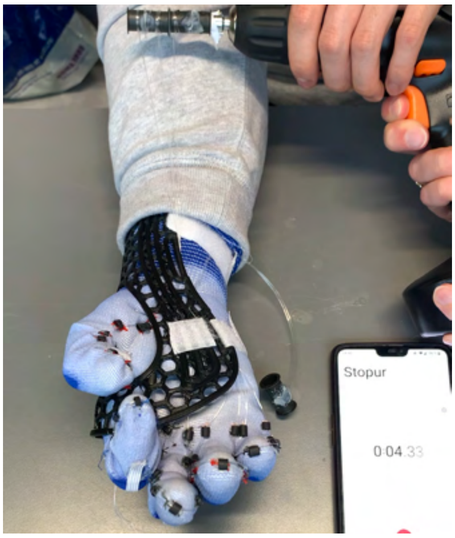
ill. 67. Benchmark: manual grasp

Mock-up testing: Hand closure speed

The hypothesis is that the speed will be experienced and perceived differently when the person is not actively moving their muscles themselves but are controlled by an external product.The test was done by utilising the analog functioning prototype by attaching a drilling machine to the wires which would then spin and pull the artificial tendons and thereby create movement. The thumb and pointer were the two fingers used in the test. The test was done on two well functioning test subjects who provided feedback throughout the test.

Mock-up grasp
This test was to experience the speed when a body part is moved by an external object. The test consisted of three different grasp-tests: closing the hand around air, cylinder grip and pinch grip. This was done to simulate IADL actions and explore whether there would be a difference between the experience of speed when introducing an object.

Close hand, no object

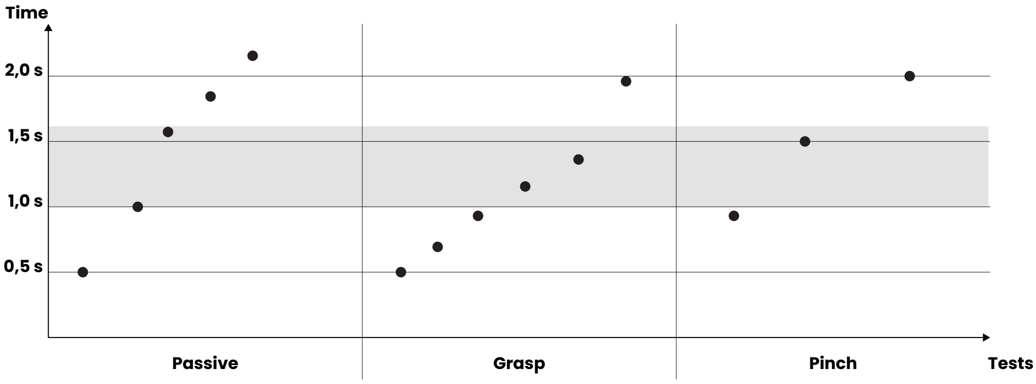


Grasp

Pinch

ill. 68. Mock-up test: Hand closure speeds of the three gestures

The different speeds tested were summarised and visualised in a graph (ill. 69). The number of tests in the different categories against the tested speeds. Based on the feedback from the users a range could be defined which the users found most lifelike and comfortable (the marked area).



ill. 69. Speed test

It was realised that different individuals can experience the same speed very differently. When closing the fingers around thin air the faster speeds were desired as those resembled the natural movement the most. However, when gripping an object the speed was perceived differently since the subject was aiming and needed more control, which made the slower speeds more acceptable and desirable.

"I felt I could better control and adjust my finger position a bit before the grasp happens so I wouldn't drop it (...) the better the speed mimics my natural speed, the better it feels".

User on a 1 second closure speed

Due to having many sources of error on the mock-up, the result was divided with a factor 2. From this test it became evident that the product should not have a pre-programmed speed but rather opt for a speed range which would benefit a diverse user segment. The speed should range between 4,2cm/s and 2,2 cm/s. The user would spend approximately 1 second to perform a hand gesture at the fastest speed and 2 seconds at the slowest speed.

Speeds are experienced and perceived differently by different individuals.

c25: Should enable speeds in a spectrum between 4,2 cm/s and 2,2 cm/s.

Conclusion

Different individuals experience speeds differently. Factors such as age, cognitive ability and well-being may have an impact on this experience but ultimately it comes down to the user's preference. Because of this, it was decided that a range of different speeds would benefit the product more than one set speed to target a broader user segment. This speed will be the first estimate for the product, however it should, for further development, be tested in more quantitative measures to pinpoint an exact favourable speed. Preferably in various scenarios to fully represent the lifelike movement speed of the hand. Furthermore, the team reflected on the fact that different fingers might require different speeds in the future, which will influence the order sequence of each finger flexion.

System architecture

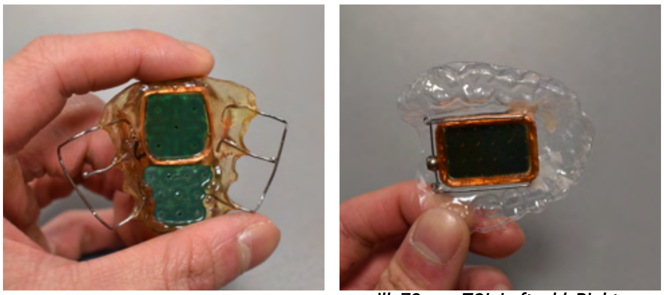
Introduction

All of the required functional aspects have been determined in order to create a product that can enable the identified hand gestures for everyday use. Therefore, the thesis team proceeds to make initial consideration to how all of the functional components work in relation to each other.

Control interface

Throughout the movement, the speed of the hand varies slightly. The first phase of the grasping, in which the hand is nearing the wanted object, the speed is significantly slower than when near the object and ready to close. Ultimately, after identifying grasping speeds, the grasping motion was closer to 0.5 s. This benchmark test was conducted as a baseline for the natural motion and which speed the team should expect to strive towards.

It is expected that different users will have different interface preference based on their level of mobility, which leaves the option to create a modular solution where the interface can be easily replaced or updated. Therefore, this choice is not necessarily final but something that should be altered to provide the best possible experience for the user. However, for this project, this control interface is a good case example.



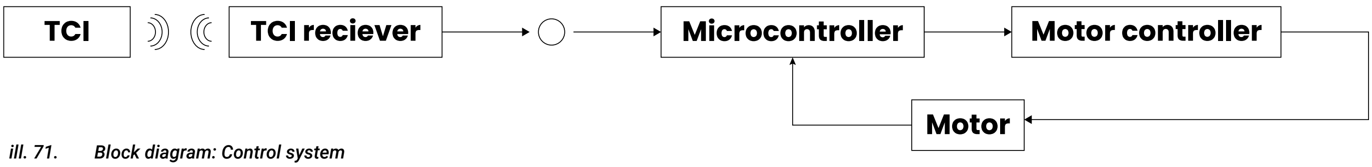
ill. 72. TCI. Left: old, Right: new

ill. 70. Control experience inspiration

Controls: Interaction between active and passive actuation

To make the learning curve of the product as easy as possible, the controls were kept simple, when performing the three commands. The desired interaction can be compared to that of a wireless controller of a gaming console. A simplified version of the desired interaction is visualised in a basic closed loop block diagram.

1. **The user presses a button**
2. **The tendons then activate the fingers needed to perform the gesture.**
3. **The user holds down the command until they are satisfied with the finger position and/or grip.**
4. **When they release the command, the fingers stay locked in place.**
5. **To return to the resting position, a release command is pressed.**
6. **When releasing the gesture, the tendon actuators return to their starting position. Here, the woven elastic band helps the fingers return to the desired resting position through passive actuation.**



ill. 71. Block diagram: Control system

Conclusion: Priority in components

As of now, there are three primary parts of the product. The thesis team decides to prioritise these parts differently for the purpose of this project. Of course, all the parts are equally important but the focus points lie where the team evaluates they can provide the greatest value for the user and innovate in relation to the problem statement:

Highest priority: The glove
The 'glove' which contains the identified elements from this phase. This part is prioritised highest as number 1 because it delves the furthest into all aspects of the holistic view. The team determines that this is where the product can differentiate itself the most from the current market in a positive way to become easily implementable in everyday life.

Second priority: Actuation
A module that contains the electronic components allowing the product to function that as of now has not been delved into.
This part is prioritised as number 2 because it is essential for the product to work but does not have as large an impact on the overall experience of using the product. The team determines they will only cover the essentials for this part for the product to function as intended.

Lowest priority: Interface
A control interface which the user uses to control the product.
This part is prioritised the least, as number 3, because it will likely be outsourced. In the initial plan, the interface will be the TCI but depending on the scaling possibilities to other user segments, this can vary to best fit their needs.

Design brief 2

Problem statement

How can the design of an exoskeleton-hand be optimised to fit into daily life by enabling tetraplegics to independently participate in social activities and provide a personalised experience that aligns with their individual identity?

Value proposition

An exoskeleton as personally tailored and essential your own spectacles.

Project Criteria

Criteria for the product solution has been categorised and implemented based on the Kano Model of customer satisfaction. The method was chosen to provide the team with a more transparent overview of the collected criteria and a way to identify which are must-haves and which are nice-to-haves. The Kano Model has separated the requirements into Performance, Basic and Delighters. Further in the report, the team will utilise this method to collect upcoming criteria in all the explored categories being Function, Application and Aesthetics.

	Performance	Basic	Delighters
All	C12: Should be aesthetically customizable C3: Must be fitted for the home-scenario C2: Should provide higher independency C9: Should dissociate from hospital/ rehabilitation equipment C14: Should enable the user to perform three hand gestures: the grasp, pinch and point.	C1: Should be applicable across different genders and age C11: Should fully control the movement C15: Should be easily implementable into the life routines C5: Should be fitted to and account for the wheelchair. C13: Must not hinder the user's existing movement capabilities.	C10: Should be fitted an individual user identity C8: Should be able to be worn under a jacket. C7: Should take up minimum space. C6: Should be lightweight. C4: Should not be removed too often in a day.
Glove	C17: The DIP, PIP and MCP joints should bend approximately simultaneously. C24: The material needs to be slightly stiffer where the tendon sheaths are placed. C16: Should use tendon actuators.		
Brace			

Specifications

Some criteria defined in the last phase have been specified further into requirement specifications and are collected throughout the process.

Part	Performance	Metric
Glove	C18: Should provide a passive resting position of 30 degrees in passive mode.	Celcius
	C21: The woven elastic element should be anchored at the DIP joint and edge of the wrist.	Cm
	C23: Tendon sheaths are placed only on the lower side of the finger running along the sides.	N/A
	C25: Should enable speeds in a spectrum between 4,2 cm/s and 2,2 cm/s.	cm/s
	C19: Tendon sheaths are placed as close to the finger as possible.	N/A
Brace	C22: The brace locks the thumb in an 80 degree abducted position.	Celcius

Phase reflection

Project overview

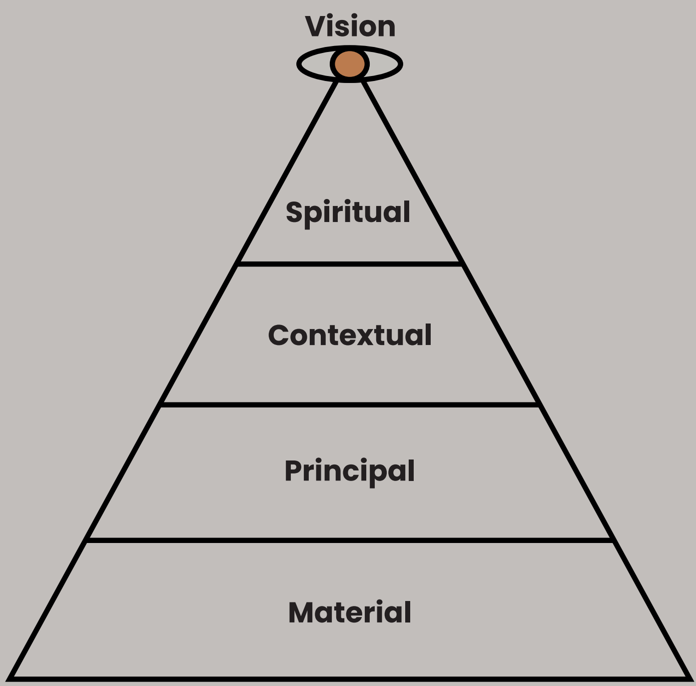
The team has identified which working principles are necessary to make the product function. Different actuation principles and setups have been explored to mimic natural movement to a sufficient degree. These resulted in three working principles: active flexion, passive extension and stabilisation of wrist and thumb.

As the team does not have the resources to produce a functional proof of concept, problem slicing was used to split the problem into easily tested and replicable principles.

The pyramid model

This conceptualising phase focused primarily on the more tangible aspects in the contextual and principal levels of the pyramid model. Metaphors were created and used from the spiritual level to visualise the interaction vision for the product. These metaphors were derived from past explicit and implicit needs from the users to fit the vision of the project.

Working with the metaphors as the baseline, principal solutions were identified using mock-ups and testing that could reach the interaction vision. This progress pushed the project a step closer towards achieving the vision of a holistic solution.



ill. 73. (Lerdahl, 2001)

Application

Phase 4

This phase navigates the applicable perspective of the holistic model. It focuses on exploring the use outside of use, meaning elements not directly tied to the function but rather aspects such as hygiene, don and doff, and mounting that are equally crucial for a successful implementation into everyday life. Problem slicing is used to split the problem into different aspects and the solution space is further detailed through iterating mock-ups and tests.

Experience benchmark

Introduction

The application aspect relates to the daily use scenario, and should therefore inspire to become equal to other things used everyday. The goal is for it to become a natural part of a routine, where the interaction will be second nature. The team must therefore explore this interaction interface and affordance should be to make it easy to decode. An over-complicated interaction would make the product troublesome to use, which could lead to abandonment.

Benchmark metaphors

The product will never be natural in the sense that it is not part of the user's body. However, it should be designed to mimic natural movement to a sufficient degree where the user and their surroundings does not recognise they are using an assistive device. To achieve the desired user experience, metaphors are set up that describe how it should feel and be perceived when in use. This was done to, internally in the team, align the common understanding of the experience vision by visualising it.

Familiar

Wearing it should feel familiar as a loved well-worn pair of hiking shoes, moulded by time and adventures.

ill. 76. Familiar hiking boots

Comfortable

It should feel as comfortable as going to sleep in newly washed cotton bed sheets, crisp and fresh.

ill. 74. Fresh bedding

Effortless

The interaction should be effortless as a well-rehearsed dance routine, where doing it feels like second nature.

ill. 75. Dancing

Problem slicing

Introduction

As the focus is to integrate the design proposal as a clothing item with the abovementioned interaction vision, several factors could get in the way of achieving this. The identified problem-areas were assessed as some of the most vital to approach to meet the criteria for the product. They were based on likewise factors which are relevant for all everyday items worn on the body.

How to take it on/off
The time it takes to put on and take off was one of the main user requests, as neither wanted to spend too much time doing this.

Daily hygiene
When worn as a piece of clothing and constantly in contact with the skin and germs, keeping the glove clean could be an issue. If the product is not possible to keep clean, the user will reject it, since it will be uncomfortable and embarrassing.

Adapted to the wheelchair
Since the users are in a wheelchair, the product needs to accommodate for this (c5), which was furthermore a user criteria. The product must not get in the way or hinder the user from driving it safely.

Hygiene

Introduction

As the product seeks to use a clothing-like approach, a tremendously significant aspect is hygiene and washing. The product should be easy to keep clean and not disrupt the user's existing washing routines to a large degree. Therefore, the product is explored from a hygiene perspective to determine which aspects need to be considered to be fitted into everyday life.

Test: Wearing a glove for 2 hours

To explore one of the identified barriers: the comfort aspect (pp. 22), and experience how it would feel to wear the product for prolonged periods, a test was conducted where the team members wore a glove for 120 minutes while continuing their daily tasks. The used glove is a gardening glove made of elastane and nylon with the palm being dipped in polyurethane coating.

Sensory feeling
Before starting, the thesis team has a hypothesis that it would become irritating to wear the glove for the duration of the test. However, due to sensory adaptation, the brain filters out the constant touch of the glove so as to not overstimulate itself (Khan Academy, 2015). However, the team noticed the importance of having a fitted glove. When wearing an ill fitting glove, the more difficult it was to perform everyday tasks and ignore the sensory stimuli.

The product needs to feel clean in addition to being visually clean.

c26: Needs to be form fitting.

Comfort
The tests also set initial requirements to the comfort of the material. Here, comfort can be split into several parameters that need to be fulfilled. Initially, the team hypothesised the glove would cause the hand to become clammy during use. Contrary to this, the hand was not sweaty in the least yet still a bit warm. Moisture wicking and temperature regulating properties will also aid in heightening the wearing experience.

c27: The material needs to be breathable.

c28: The material needs to be moisture wicking.

c29:The material needs to be temperature regulating.

ill. 77. Wearing a glove while working

ill. 78. Close-up: Wearing a glove while working

Clothing layer hierarchy

As the product should be worn daily, it needs to be able to be cleaned to stay hygienic. Many existing exoskeleton products do not consider existing routines and end up adding more steps or disregard hygiene altogether. Therefore, it is explored how the product can be integrated into daily routines in a way that makes sense for the user.

Sensory feeling
The product takes a clothing-like approach. Therefore, it is looked at how we wear clothing and which routines are done to keep them clean. There are different layers to clothing. The closer the layer is to the skin, the more often it is usually washed with some clothing articles requiring more washing than others; undergarments, socks and the like (REI, 2023).

- A base layer is in direct contact with the skin and wicks off sweat.
- A middle layer provides heat.
- An outer layer shields the user from the surroundings.

The product falls under the base layer category as it is in direct contact with the skin. Simultaneously, it also needs to adopt properties from the outer layer as it will also be the contact surface to the surroundings. Being in contact with the skin means it is affected by sweat, body oils and the friction of the skin. To this, excessive usage of unclean clothing articles can have a severely detrimental impact on the user, their body and others.

Worst Case scenarios

The following worst case scenario was identified to map out what elements the glove needs to withstand (see apx. 18 and 28). The hygiene aspect is multi faceted. There are reasons primarily affecting the user such as germs and skin problems, and there are elements such as odour and visual uncleanliness like stains that may worsen the perception of the user. In the broader scope, these are all linked and come down to being able to properly wash the product.

1. Accidental spill.
2. Sweating (odour).
3. Sand, crumbs, dust.

Conclusion

To accommodate both being able to wash and clean the glove, while still remaining considerate of the electronic parts, the glove is split into two. This working principle was inspired by skiing gloves, where a glove liner is added to provide additional heat and comfort. Furthermore the principle closely relates to a sock in a shoe hierarchy, where the shoe provides the function and the sock being the protective layer.

This concept-idea affordance of how to wash and keep it clean would be highly familiar for the user, and communicates the dominant relationship between the glove and liner. To fit into everyday living, the inner layer should be machine washable like the user's other clothing articles. The outer does not necessarily need to be machine cleanable but needs to be easy to clean before use; contact with food, the user's face or other people.

ill. 79. Glove liner 1

ill. 80. Glove liner 2

1. Accidental spill

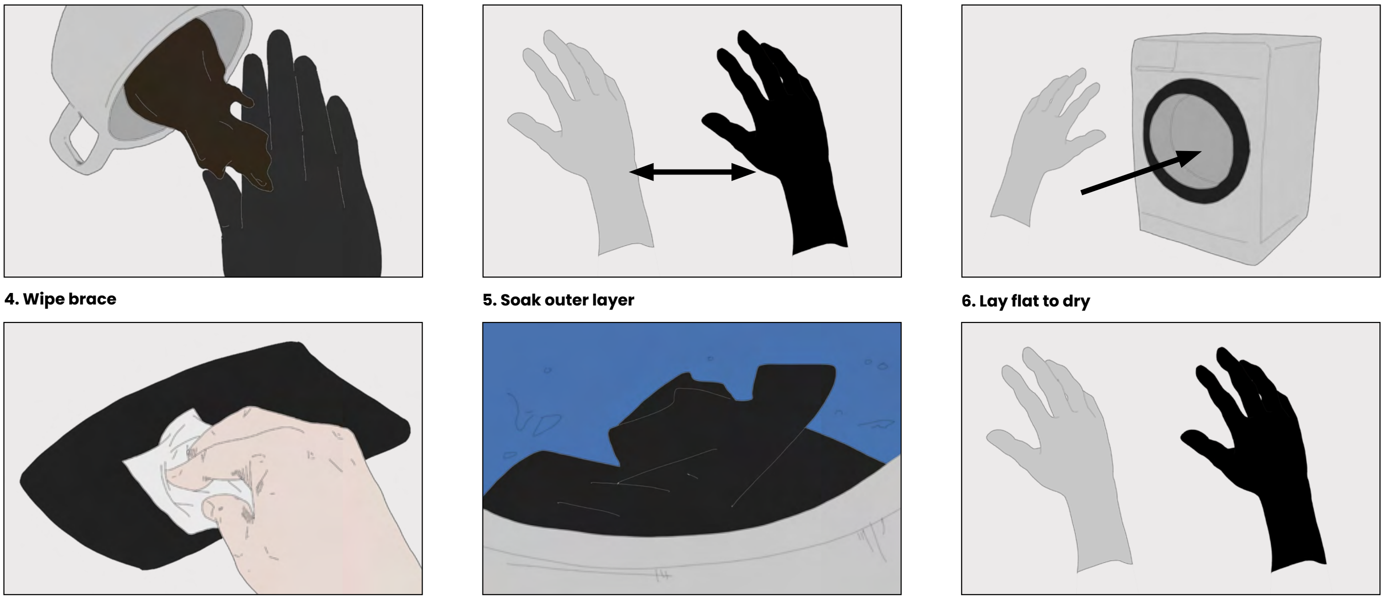
2. Seperate layers

3. Inner layer in washing machine

4. Wipe brace

5. Soak outer layer

6. Lay flat to dry



ill. 81. Washing scenario

c30: The glove liner needs to be machine washable.

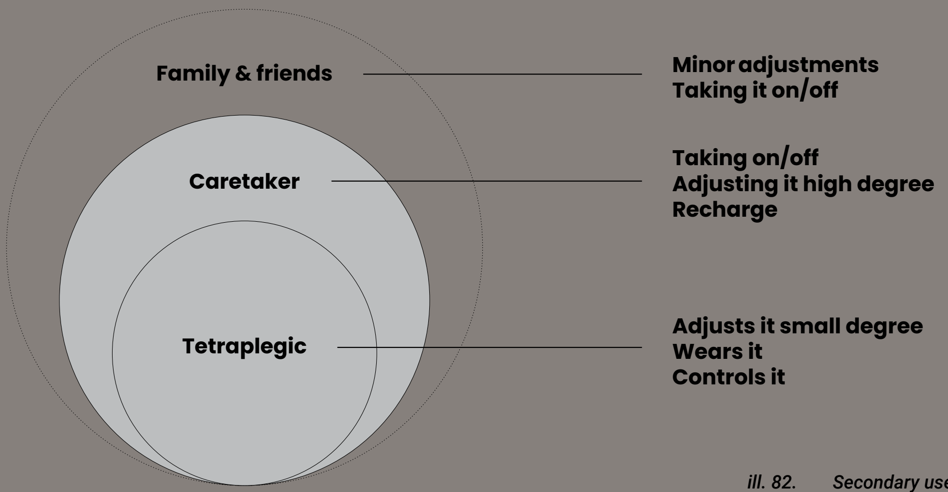
c31: The inner layer needs to be able to withstand direct contact with sweat and body oils.

c32: The outer layer needs to be wipeable with disinfectant.

Don & Doff

Introduction

Don and doff refers to how the product is taken on and off and which steps it involves. For the user group, it is incredibly important that it is easy and quick to do. They tend to avoid products that require significant don & doff time given how often they may need to do it during an average day. In addition, many individuals from the user group are unable to perform this task themselves and therefore the process should also take a caretaker into consideration.

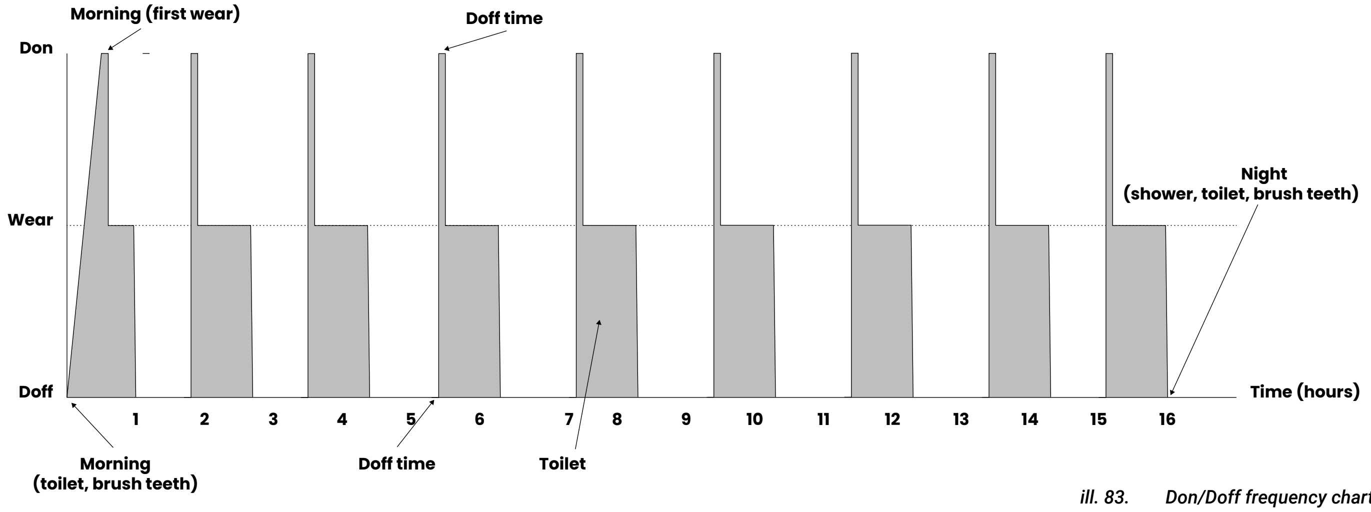


ill. 82. Secondary users

Don & Doff frequency during a day

To gain further insights into the everyday scenario, a don & doff frequency chart is set up to visualise the amount of times the product would need to be taken on and off during an average day. The chart is based on desktop research combined with the team's own experience. The team was aware of the possible sources of error in the chart, since this is influenced by many factors, however it was deemed relevant to get an overall picture of an average day. (see apx. 24)

The chart assumes the individual is awake for 16 hours. Based on existing literature, the average individual urinates approximately seven times a day. It is also assumed that the individual will shower once a day. An additional two don & doff cycles are put in to accommodate for other activities like rehabilitation, sports and the like (Bajic, 2021; Bladder and Bowel Community, 2021).



ill. 83. Don/Doff frequency chart

The product will be taken on and off approx. 10 times a day.

Some of the daily activities requiring a don & doff cycle overlap.

Brace tightening principles

It has been identified that the product needs to be donned and doffed, or vice versa, every two hours on average. Therefore, the team looks into different options to make this process as quick as possible.

Looking at the product, there are three elements on the hand: an inner layer, an outer layer and a brace. The brace is the outermost layer and by tightening this, the entire construction will be secured. Because of this, the closing principle will be only applied to this part. One of the identified barriers (p.22) is fit which is why the closing system should be adaptable to many different wrist and hand shapes.

To ensure a proper, comfortable and stabilising fit, the brace needs to be able to be tightened around the wrist. The closing mechanism should be as easy for both the user and a potential caretaker as possible. To decide on a system, several options are laid out and evaluated morphologically. The following possibilities were chosen by the team based on familiarity, sourcing opportunities, application, ease of use and the relation to everyday clothing scenarios.

Velcro

ill. 84. Velcro

Laces

ill. 85. Laces on pants

Dial lace lock

ill. 86. Dial lock

Lock lace

ill. 87. Lace lock

A morphological analysis of the different systems was made to determine which fulfilled the requirements to application and functionality the best. The experience-dimension and aesthetic qualities of each will be determined through mock-ups and user tests. The following topics (left-most column) highlights the points of interest if regards to application and functionality in a daily scenario, and each system was described on each level (see apx. 29).

Velcro				
	Velcro	**Laces**	**Dial lace**	**Lock lace**
Ease of use				
Repairability				
Lifetime cycles				
Ongoing adjustability				
Don/Doff time				
Tight fit				
Aesthetic association				
Ergonomic difficulty				

Mock-up: Closing principles

The three that scored the highest in the analysis were mocked-up to test out the user experience and tightening qualities. The thesis team could not acquire a dial lock in time for the mock-up test, but sourced a cycling shoe through a field study with the exact principle as proof-of-concept. The mock-ups were tested on test subjects to get feedback on the experience and aesthetic values in everyday scenarios (see apx. 29).

Velcro

Velcro is a very well-known closing mechanism. It is easy to use even with limited mobility. The experience is intuitive, quick to do and easy to adjust in tightness. Despite being a simple use case, velcro also makes a very distinct noise that some find unpleasant.

"I think the crunchy sound of velcro is the sound of low quality."

ill. 88. Velcro

Velcro	**Advantages**	**Disadvantages**
Aesthetically	Invisible design Smooth looking **Many colour variations**	**Crunchy sound** Cheap looking
Usability	**Easy to lock** One-hand application Can be adjusted	**Sticks to clothing** Requires smaller adjustments **Hard to tighten evenly**
Application	**Easy to replace** Can be washed	Fast wear and tear Easily gets dirty **Short lifetime (cycles)**

Laces

Laces are a commonly used principle in shoes, drawing associations to everyday life. It gives a sleek look. The lacing itself provides a very comfortable fit that is easy to regulate during the initial lacing. On the other side, manual lacing is particularly cumbersome with low mobility and practically impossible with only one hand.

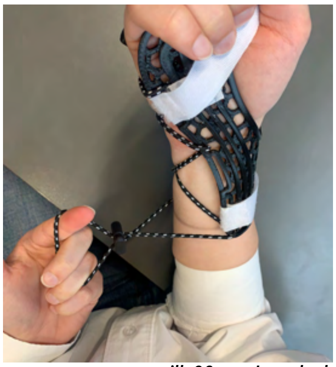
"I feel like it would be too hard to use and after a while i would be tired of trying it so often"

ill. 89. Laces

Laces	Advantages	Disadvantages
Aesthetically	Change in colour	Looks too clothing like **Doesn't look strong**
Usability	**Known mechanism**	Impossible to tie with one hand **Long time to tie** **Will loosen over time**
Application	Easy to replace **Can be washed** Ling lifetime High strength	-

Lock lace

The lock lace is a lace-reliant system. To tighten the lacing, the user simply pulls the "pull tab" to their preferred fit. To loosen it, the user opens the "lock" by pressing down on it. This type of locking mechanism is incredibly fast to tighten and loosen due to the simple construction. It is practically impossible to tighten with one hand. Conversely, it is easy to loosen with one hand.



ill. 90. Lace lock

"I don't like the idea of having a mechanism often used for the feet on my hand, i feel like there should be a differentiation"

Lock lace	Advantages	Disadvantages
Aesthetically	Change in colour	Looks too clothing like Doesn't look strong **looks cheap**
Usability	**Known mechanism**	Impossible to tie with one hand **Long time to tie** **Will loosen over time**
Application	Easy to replace Can be washed Ling lifetime **High strength**	-

Dial lock

The dial lock is a lace reliant system that uses smaller wires than traditional lacing. To tighten a product with a dial lock, the user simply needs to press down the top of the lock and turn the top clockwise. It can be loosened by turning the top counter clockwise. To completely release the system, the top is pulled up.

ill. 91. Dial lock

"I think it shows that the company deeply cares for the users and considers the everyday use of the glove. It highlights that you didn't just choose the cheapest option."

Dial lace	Advantages	Disadvantages
Aesthetically	**Very subtle** High quality **Seems professional** Very minimalistic	Bunches of the wrist **Can be too big**
Usability	Easy to tighten **One-hand movement** Can be done by yourself or another Clear affordance Micro adjustments Easily re-tightened	Might not feel tight enough Can accidentally be loosened can get stuck in clothes
Application	**Easy to replace** Can be washed **Long lifetime** High strength	Harder to replace **Risk of water or dirt damage** **Expensive**

Some design details give associations to medical devices.

Conclusion

After evaluating the different options, the dial lock was chosen. From the morphological analysis, velcro and the dial lock were the best contenders, but there was a great price gap between the two. Yet, the dial lock lace is chosen as it provided the best feedback from test subjects, it fits the product well in its minimalistic appearance, it has intuitive affordance, it can be exchanged/fixed, and it provides trustworthiness and a feeling of quality.

Test: Don & Doff time

Introduction

During the user interviews, Lars and Hanne mentioned that one of the biggest deal breakers for them would be if the product took too much time to be put on as they would likely do it multiple times a day. Despite not having the dial lock at hand, the thesis team still deems it relevant to test the time required for donning and doffing.

Moulding a brace

The brace that was previously 3D printed did not provide an as snug fit as desired, and because of that a new brace was made. This time, it was chosen to use gauze plaster and sculpt it to fit perfectly around the hand. This would also give a better picture of how the final design of the brace would fit.

After the gauze had set, it had to be cut open to allow the hand to slip out. It was chosen to cut it on the outer side as this would make it easiest to apply and tighten for a caretaker. Furthermore, it was cut to accommodate the needed thumb position and allow the thumb to flex. A wire was led through holes to imitate the lacing.

ill. 92. Brace moulding process

Don & Doff time

In spite of the sources of error like friction between the materials and handling a fragile brace, the test gave a good picture of how this process could look for an unpracticed individual. The doffing took significantly less time than the donning as every part could be pulled off simultaneously. Regarding the donning, the test gave many insights. For the team member, this was the first time they applied a glove(s) and brace on another individual. It is assumed the caretaker would become more proficient at performing the task every time, eventually cutting down the required time significantly. The dial lock would also reduce the time required comparatively to tightening the laces manually as done in the test. The materials used in the inner and outer layers should be as frictionless against each other as possible to ease the donning process. This in addition to a better fitted glove would make the experience less cumbersome.

In total, the time it took during the test was 3 minutes. It is speculated this time could be reduced to approximately 2 minutes with the correct construction and more experience.

Inner **Outer** **Brace**

ill. 93. Don & Doff test

Reflection: Better wearing experience

It was discovered during the mock-up tests of the closing principle that the outer layer had a tendency to bunch up. For this reason, it was decided to implement snap buttons that could hold the outer layer in position. The tightness of the entire product could then be controlled through the dial lock on the brace. This way, the layers would seem more integrated despite being essentially interchangeable.

Conclusion

A dial lock was chosen as the closing principal due to being quick to tighten/loosen, easy to regulate and giving associations to high quality equipment. After experimenting with brace fittings, it was discovered the brace needs to be form fitted specifically to the user to provide sufficient stabilisation and comfort. Finally, the ideal donning time of 2 minutes is deemed fast enough to not become too cumbersome to perform multiple times a day.

Reflection: Further development

The result was not as desired, as the team would like a don time of about 1 min. For further development, exploring and perfecting the ease of the don and doff time would be of high priority to raise the value of the product,, but due to the timeframe of the project, this was not explored further at this point.

Mounting

Introduction

Besides the glove of the product, there also needs to be an actuation module which houses motors, battery and microcontroller. The unit needs to be mounted somewhere on or near the user and can not be placed somewhere with the possibility to limit movement or get in the way of the wheelchair.

Mounting possibilities

The thesis team brainstormed different options for the placement of the actuation module, which was mocked-up and tested.

Wheelchair
As Lars and Hanne use a wheelchair daily, it was a logical conclusion to make an universal interface that could latch onto the railing of different wheelchair models.

On the belt
The actuation module could be placed on the hip by latching onto a belt. This way the module would be more hidden, however the cord would be in front of the user and could disturb.

Upper arm
Another method is to attach the module on the upper arm so it lies closely to the glove but does not weigh the arm down significantly. This is deemed the most coherent solution with fewer risks of getting tangled onto something.

ill. 94. Wheelchair

- Risk of cord getting stuck
- Must fit to different wheelchair types
- Can not easily be brought to a couch
+ Weight is removed from the body
+ Components are hidden

ill. 95. On belt

- Cord in the way
- Uncomfortable to wear
- Should be small
+ Can be brought to eg. a chair

ill. 96. Upper arm

- Should be small
+ Cord does not get in the way
+ Coherent look to the rest of the product
+ Can be brought to eg. a chair

c33: The actuation module must not exceed 10*15 cm.

Conclusion

Based on this idea and exploration it was decided to continue with placement on the upper arm, as this was seen as the most versatile and agile solution. The cord would then have to be measured to the length of the user's arm when produced. This would need to be done to provide a tailored fit where the cord does not get in the way when performing daily tasks. To make sure the actuation module would not be too big to seem intrusive on the arm, a dimension criteria was set.

Design brief 3

Problem statement

How can the design of an exoskeleton-hand be optimised to fit into daily life by enabling tetraplegics to independently participate in social activities and provide a personalised experience that aligns with their individual identity?

Value proposition

An exoskeleton as personally tailored and essential your own spectacles.

Project Criteria

Criteria for the product solution has been categorised and implemented based on the Kano Model of customer satisfaction. The method was chosen to provide the team with a more transparent overview of the collected criteria and a way to identify which are must-haves and which are nice-to-haves. The Kano Model has separated the requirements into Performance, Basic and Delighters. Further in the report, the team will utilise this method to collect upcoming criteria in all the explored categories being Function, Application and Aesthetics.

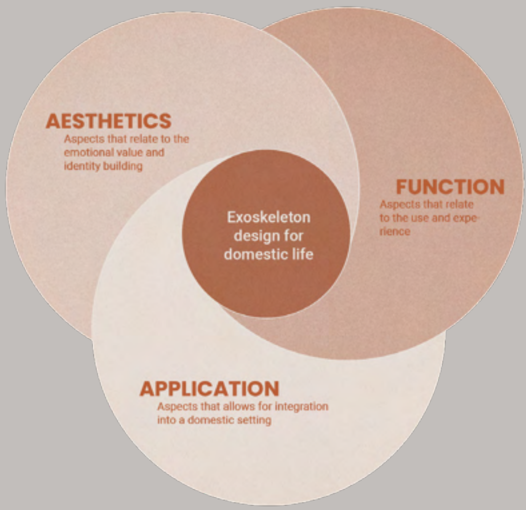
	Performance	Basic	Delighters
All	C12: Should be aesthetically customizable C3: Must be fitted for the home-scenario C2: Should provide higher independency C9: Should dissociate from hospital/ rehabilitation equipment C14: Should enable the user to perform three hand gestures: the grasp, pinch and point.	C1: Should be applicable across different genders and age C11: Should fully control the movement C15: Should be easily implementable into the life routines C5: Should be fitted to and account for the wheelchair. C13: Must not hinder the user's existing movement capabilities.	C10: Should be fitted an individual user identity C8: Should be able to be worn under a jacket. C7: Should take up minimum space. C6: Should be lightweight. C4: Should not be removed too often in a day.
Glove	C17: The DIP, PIP and MCP joints should bend approximately simultaneously. C24: The material needs to be slightly stiffer where the tendon sheaths are placed. C16: Should use tendon actuators. C26: Should be form fitting.	C32: The outer layer needs to be wipeable with disinfectant.	
Brace			
Liner	C30: Be machine washable.	C27 Should be breathable. C28 Should be moisture wicking. C29 Should be temperature regulating.	C31 Needs to be able to sweat and body oils.

Specifications

Some criteria defined in the last phase have been specified further into requirement specifications and are collected throughout the process.

Part	Performance	Metric
Glove	**C18: Should provide a passive resting position of 30 degrees in passive mode.**	**Celcius**
	C21: The woven elastic element should be anchored at the DIP joint and edge of the wrist.	**Cm**
	C23: Tendon sheaths are placed only on the lower side of the finger running along the sides.	**N/A**
	C25: Should enable speeds in a spectrum between 4,2 cm/s and 2,2 cm/s.	**cm/s**
	C19: Tendon sheaths are placed as close to the finger as possible.	**N/A**
Brace	**C22: The brace locks the thumb in an 80 degree abducted position.**	**Celcius**
Actua-tion module	**C33: The actuation must not exceed 10*15 cm**	**Cm**

Phase reflection



ill. 97. Holistic model

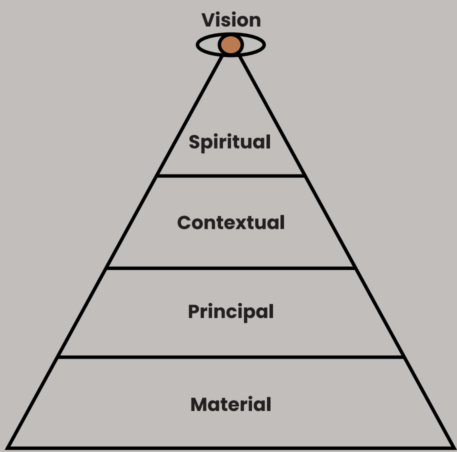
Project overview

The team has explored which aspects are essential for the product to fit into an everyday context. These primarily being hygiene and don & doff. Using principles from everyday life, the glove is split into an inner and outer layer. This change seeks to provide a better connection to everyday life as the inner layer will be easily removable and washed, acting like base layer clothing. For the don & doff, a dial lace lock was implemented due to its wanted characteristics: ease of use and an image that does not remind the users of disability.

The pyramid model

This phase focused primarily on the contextual and principals levels. As the product seeks to become part of everyday life for its users, relevant existing everyday routines were identified and used to determine working principles that could strengthen the link between the two levels; the process of washing clothes, the feeling of wearing clothing.

Acting out scenarios using mock-ups, and going through feedback loops with colleagues, were the primary tools used to evaluate and iterate on the product. Once again, the progression and changes in the solution space push the project closer to achieving the vision of a holistic solution.



ill. 98. (Lerdahl, 2001)

Aesthetics

Phase 5

This phase navigates the aesthetic perspective of the holistic model. It focuses on exploring and understanding how different aesthetics choices impact the emotional value and user fit of the product. By analysing existing products, the current state of the market is examined to locate gaps. This is to iterate on the visual appearance of the product with an eye to perceived associations, personalisation and occasion based design. This results in a final design where product details as well as function are coherent and fit the vision.

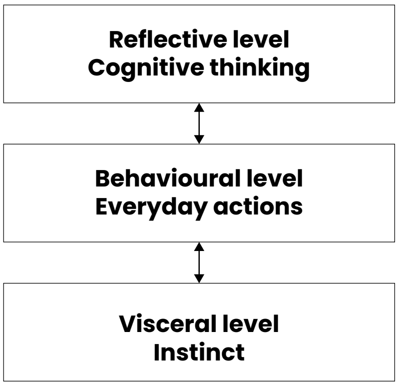
Emotional design

Introduction

A loved product is not only used due to its functionality but also because it has a personality that elicits an appropriate emotional response from its user. Emotions have a very strong impact on different users' reaction and perception of a product (Norman, 2007). But what is required to make a good visual design? For this product, the phrase "form follows function" transforms into "form is function". The aesthetics need to be coherent with the function and application to tie the product into one fluid story (Reddy, 2023).

Understanding the levels to emotional design

To better describe the wanted emotions and experience, Don Norman, in his book Emotional Design (2007), describes three levels of mental processing: Visceral, Behavioral and Reflective (Norman, 2007, p. 21-23).



ill. 99. (Norman, 2007)

Of course, all three levels affect each other to some degree but as a simplistic method of separation, these characteristics cover the primary take-aways. However, these definitions are not directly applicable to the product. Delving further into these, Don Norman proposes a simplified method of translating the three levels to product characteristics (Norman, 2007, p. 39).

The visceral level: Appearance
Both products are in the same category and have the exact same function but elicit different emotional responses / gut feelings.

ill. 100. Hand of hope

ill. 101. Carbonhand

The behavioural level: The pleasure and effectiveness of use
Both products have the same function but the behaviour in which it is used differs. The MultiRob is an extern exoskeleton whereas the EXOTIC is fastened to the body.

ill. 102. MultiRob

ill. 103. EXOTIC

The reflective level: Self-image, personal satisfaction, memories
This level is an essential part of an individual's identity, e.g. Lars and Hanne have completely different self-images due to various factors such as culture, upbringing, social circle etc.

ill. 104. Lars

ill. 105. Hanne

Briefly explained, the emotions a product elicits is tremendously important for how the user's perceive it. The product can be perfectly functional but if the user can not identify with it, they will never build a strong user-product relationship (Marquez, 2018).

"Our self-image plays a more important role in our lives than we like to admit. (...) The way we dress and behave, the material objects we possess, jewellery and watches, cars and homes, all are public expressions of ourselves."

– (Norman, 2007, p. 53)

Conclusion

Looking back at the product solution, the prior focus was set on the behavioural level and making the product work to a sufficient degree. However, the thesis team deem working with the visceral and the reflective level equally important to successfully achieve the vision of an exoskeleton product that can be integrated into everyday life. In very simplified terms, all this boils down to the concept of self-image and identity.

Existing market: Exoskeleton and medical products

Introduction

It has been established that a strong emotional connection between user and product is paramount for the product's market success. This chapter focuses on shedding light onto why existing products on the market fall short by reviewing their appearance, which associations they bring and what emotional response they elicit, by building on top of the initial market research (pp. 21). As two of the identified barriers were customization and social acceptance, it is investigated what it takes to positively distinguish the product from its competitors.

Anti-styleboard

Both medical/rehabilitative equipment and existing exoskeleton designs both included elements that were undesirable as explored in phase 2 and 3. Both areas were unfolded further in an anti-styleboard, which visually represented what the design proposal should avoid. This was used in the development on the visceral level as a reference of what to steer away from which would light a clearer path toward a desirable outcome.

Reflection: Breaking the design fixation

As a result of a long thorough market research phase, the team was highly fixated on product solutions and features already represented on the market. The anti-styleboard was made to encourage the thesis team to think more outside the box and push the design development in accordance with the vision to truly "redefine the way we own and use exoskeletons".

1. EXOTIC

ill. 106.

Very **visible mechanisms** make the product look unfinished and designed for a lab-context.

2. Myopro

ill. 107.

Voluminous constructions look **intimidating** from an outside perspective and do not look fitting for use outside of a **rehabilitation centre.**

3. Neomano

ill. 108.

There is **a lack of colour options**, making it hard to personalise. CMF aspects are often **cold** and **masculine**.

4. Carbonhand

ill. 109.

Product is clashing with the user's outfit and the contrast draws the eye to the product at first glance.

5. Thumb splint

ill. 110.

The **velcro** bands draw association to a temporary and functional use designed for injury.

6. 3D printed cast

ill. 111.

The continuous form makes a bulky appearance which does not follow the flow of the arm and wrist.

7. Syrebo hand

ill. 112.

Stark and bright contrast colours makes it look **playful and cheap.**

The power relationship will become skewed if the product is dominant.

The product needs to be able to adapt to the user's wardrobe.

Conclusion

Looking at existing products: exoskeletons and medical devices, it is evident that most are a user misfit designed for temporary use. Taking emotional design into account, the user needs to adapt to these products and not vice versa which can be a large factor in preventing a meaningful bond and ideal power relationship between user and product.

Current designs follow a very clear "form follows function" ideology by borrowing working principles from rehabilitative equipment and allowing the mechanical and functional structure to define the overall product language. Purely aesthetically, for most individuals the products are a "one size fits none".

Current aethetic framing

The old aesthetic framing, based on the current standpoint on the market, showcases a misfit between the working principles and the found insights and aspired value the product should provide. This leaves a yet undefined framing. The new product image and supportive working principles will be explored in the following chapters to define the new aesthetic framing.

Occassion-based design?

Introduction

Some of the primary barriers defined when introducing an exoskeleton into daily life were: lack of customization and a social acceptance. This chapter unfolds what it could mean to wear exoskeletons like clothing and which working principles and languages could be adapted.

Occasion-based design and formality

Looking back at the visceral and reflective levels, the product needs to play into its user's self-image. Material objects are a large part of how humans express themselves in public settings (Norman, 2007). The product therefore needs to be somewhat adaptable to different scenarios and occasions in our social lifes. One primary occasion spectrum is the one between levels of formality, which both relates to the occasion we are attending and the personal preferences in regards to self-image.

Shoes as the inspiration
Keeping the user's physical capabilities (pp. 18) and the identified use scenarios (pp. 16) in mind, three different occasion types are identified that cover almost every need. These occasions are investigated with the purpose of identifying which design features characterise them. For the purpose of creating a wearable product, male shoes in a nordic design language were used as the reference.

Users do not mind getting them dirty. Mat and textured, and perhaps in a playful colour or pattern.

Sleek and refined with smooth and shiny surfaces. The darker and richer colours are generally perceived as more elegant.

ill. 113. Formality level using shoes as the inspiration

From this, it can be concluded that CMF composition has a great influence on how formal a wearable piece is perceived. The analysis highlighted the addition of colour would provide a different spark and energy to the product regardless of its formality or intended use. Colour could make it pop and eye-catching or sleek and downtoned. Even the most perceived formal shoe, would lean towards casual should it have bright colour accents.

Part conclusion

It was therefore decided within the team that the preferred position would be towards high formality as a base, but with the option of adding colour as a way to freshen, casualise and overall characterise the look. This was seen as the most versatile solution where the users could customise themselves within the range of occasions. The next step is therefore to explore how colour can be added to the design and made customizable without compromising the functional and applicational principles.

Reflection: Shoes and gloves & Freedom of choice

Shoes were chosen as an example, since the team was redundant to choosing gloves, because of the risk og design fixation. However, the CMF of shoes are made on a different foundation of functionality and therefore the categorization might not be directly applicable, but was insead used as a way to visualise a spectrum.

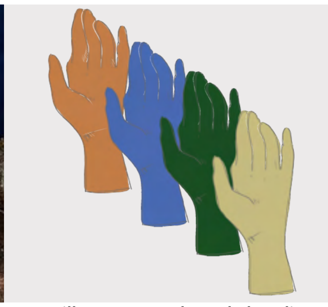
It should also be noted that the line between each formality level is blurring as the years pass by. People enjoy flexibility and freedom in their choices and the design of this product proposal is therefore not placed in a specific category, but rather for all occasions. Furthermore, as the spectrum here is based on nordic fashion, it might look very different in other cultures.

Colour addition exploration

It was now explored how to implement colour options into the design to make it occasion-based. This was explored through a brainpool sketching session, where the team assessed and discussed the different pros and cons of each idea. Some ideas were to sell more gloves to the buyer, others included interchangeable parts of the brace, but those was rejected because of cost and the cumbersome process involved.

It was instead chosen to work with the elements already in the design, instead of adding new. The choice was therefore to implement a layered design technique, where the inner glove liner should be made visible through the glove itself and the brace. Inspired how a colourful sock can casualise a formal shoe. And make the inner glove fill the role of a sock. The final choice was to make a cutout in the glove and brace to let the glove liner be seen through it. This design idea should be detailed further to explore the exact principles behind it.

ill. 114. Coloured socks



ill. 115. Coloured glove liners

Conlusion

The final choice was to make a cutout in the glove and brace to let the glove liner be seen through it. This design idea will be detailed further to explore the exact principles behind it.

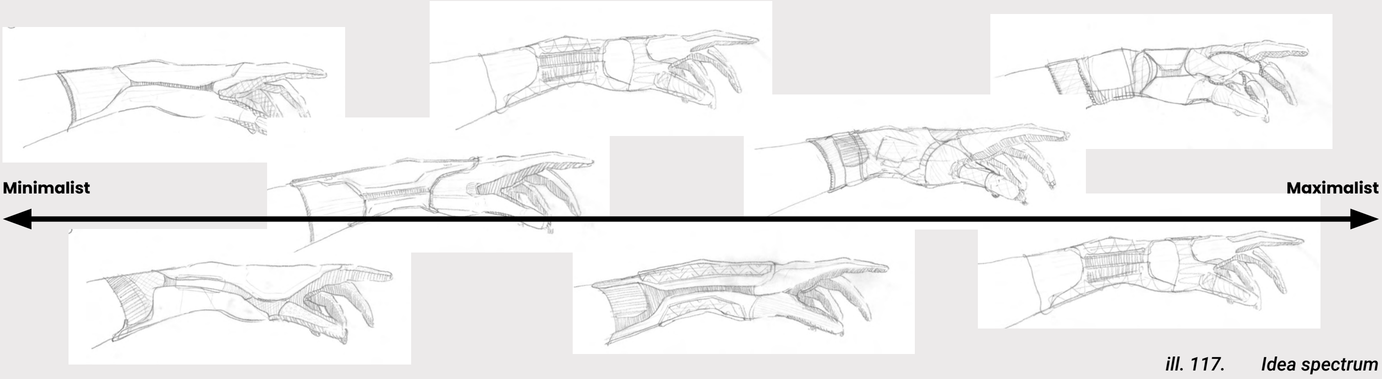
Reflection: Ease the don/doff process

The team saw a great potential in the addition, since it would also decrease the don-time, as explored in the previous chapter. The fiction surfaces between the glove and liner would be less, so it was expected that not only was this an ethical principle but also provided a functional value that the team did not see before.

ill. 116. Cut-out on glove

Ideate 1: an occasion-based design – mōtus

Using the identified information as the foundation, an ideation session is conducted. As many sketches as possible are drawn and examined using perceptual mapping (Dhiman, 2022). The sketches are evaluated in accordance to how much they push the current market: minimalistic vs. maximalistic, to identify an appropriate balance between the two. It should be noted that all concepts are clothing-like to fit into everyday life.



ill. 117. Idea spectrum

Reflection: Ease the don/doff process

The ideation process did not provide a clear result for the team to continue with. The ideas varied too much and there was no clear aesthetical path to measure the designs against. The team deemed it a necessary approach to push the industry standard as much as possible, making the view on exoskeletons change.

The team therefore needed to look into the future trends of fashion to define a spectrum for the product it fit into, which would align the ideation process.

The future of fashion

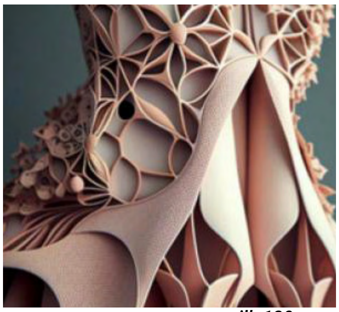
This product proposal is a visionary product of the future. Exoskeletons are not a natural part of the daily ensemble. By defining and creating a new product langage for it, it would be possible to differentiate it on the market, and fit into future trends. To answer this the future of fashion was explored. Since one can not predict the future, the AI-tool Midjourney was utilised to visualise the team's vision. Some of these images combined with finds from web-research a styleboard was defined of the desired product direction.

ill. 118.

Contrasts between massive and mesh structure.

ill. 119.

Flowy organic forms
* AI generated with the prompt: The future of fashion produced with 3d printing technology and textile, neutral colours with some accent colour, movement, high fashion, hyper realistic



ill. 120.

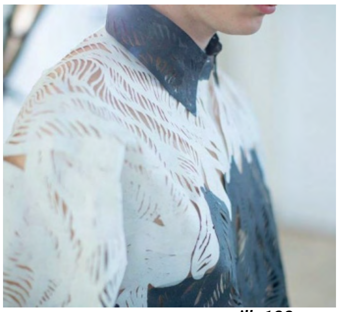
Material and surface contrasts
* AI generated with the prompt: The future of fashion produced with 3d printing technology and textile, neutral colours with some accent colour, movement, high fashion, hyper realistic

ill. 121.

Colour pops
*AI generated with the prompt: The future of a high fashion shoe produced with 3d printing and textile, generative design, grey nuances and vibrant accent colour, movement, high fashion, hyper realistic

ill. 122.

Formal mat finish



ill. 123.

Transparency through mesh

ill. 124.

Fitted and elegant on the body

Testing the limits: Couture approach

Introduction

The design team chose to take it to the extreme and diverged out as it could go to test the limits and edges of the solution space. The question was: What would the ultimate dream scenario be to get the design as customizable and as occasion-based as possible?

Couture and tailoring

This was based on an idea to create such a strong personal connection between user and product that the aspect of being able to change parts at home could be foregone. The vision for this was to provide the same experience as when getting a bespoke suit or customising a pair of shoes on a website.

Customise on all parameters
To accomplish this, the design platform is taken to an extreme. The user's level of mobility and strength level is determined during an initial consultation to determine the power level of the motor and rigidity of the brace. This is followed by 3D scanning their hand to create an individualised template for the gloves and brace. Finally, the user will be able to choose between a wide variety of colours for the inner and outer glove, as well as the colour and pattern on the brace. All these stylistic choices allow the user to showcase their personality.

ill. 125. Design platform

Colour-match your clothes on occasion

ill. 126. Occasion-based design

Conclusion

Seen in the light of a first market launch this was too extreme for a product like this. It was seen as more appropriate and feasible to make the customization options more limited with only pre-defined platforms. The pivot helped the team scope out and identify the most valuable traits to include in further development. These primarily included,

- Colour choices on the glove liner
- Only one mesh patterns on the brace
- Few colour options for the glove

Reflection: Setting the right comparison

The thesis team explored the couture approach because they were not sure if the product was sufficiently occasion-based. However, the basis of comparison was skewed. The product should be compared to other exoskeletons and not products from completely different areas. Using this perspective, the product would be tremendously occasion-based in its field even if the customizability options are reduced.

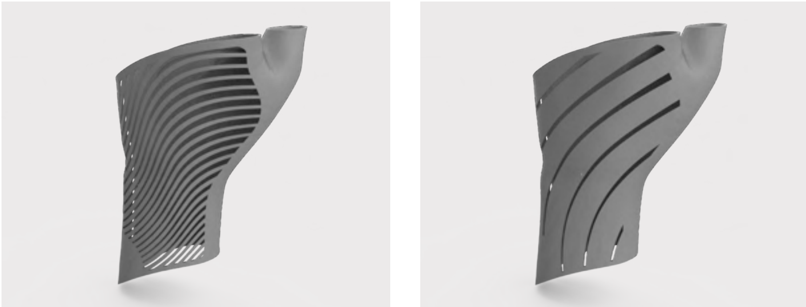
Revision of the design approach

Introduction

After reflecting on the previous iteration the team pivoted back and did a reevaluation of the design direction. This is done to lessen the risk of analysis paralysis and simplifying the product to what is deemed most essential, ultimately creating a stronger product identity.

CMF

To enhance the storytelling aspect of mōtus and tying the vision and product details together, the thesis teams decide to pursue the flowy pattern due to a strong connection to physical movement (pp. 59). The Surface finish should be a slightly textured, matte finish. The user can however choose between two different pattern densities: a low density and a high density pattern. This is done to not enforce a vision but allows the user to let their personality, and preferred inner layer colour, shine through.



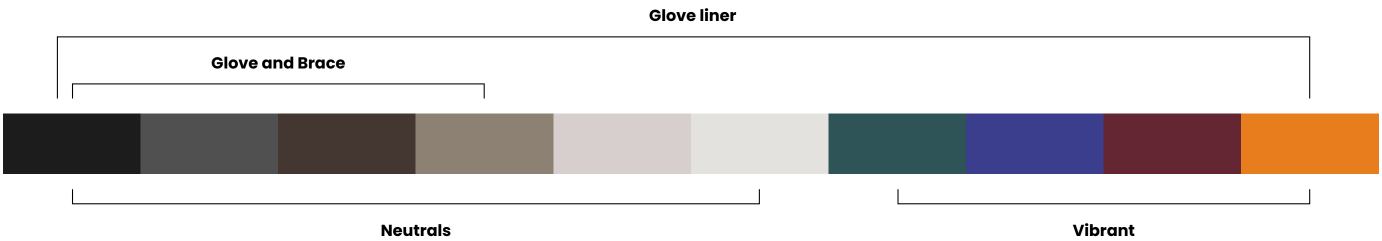
ill. 127. Brace pattern densities

How many colours are enough?

Previously, all colours in the RGB spectrum were a possibility. Now pursuing a simpler product, the options should be limited to a set of colours that would fit well with each other. After iterating on colour palettes, it was decided on a palette of neutral and vibrant, "mature" colours most would find appealing. (see apx. 28)

Glove
The colours for the glove were decided from earth tones, black and grey. This was done to represent a typical nordic colour palette and which most contrast colours would match.

Glove liner
A few more options should be available for the glove liner underneath, which will include both matching colours and contrasts. The user will be able to mix n' match a number of inner layers in their preferred colours, switching up the style of the glove.



Conclusion

After the revision, several design aspects have been cut away as to only keep the most essential design features. Through this, mōtus has been reborn. The extreme couture approach was simplified and made easier to navigate for a user. Despite no longer having the option to complete customise all parameters, the combination possibilites are still strong enough to fit any identity. A strong colour palette fits the Nordic context and brings resemblance to clothing and furniture, while the flowy pattern is used for the brace to storytell about the vision of movement.

ill. 128. The final form of mōtus

Design brief 4

Problem statement

How can the design of an exoskeleton-hand be optimised to fit into daily life by enabling tetraplegics to independently participate in social activities and provide a personalised experience that aligns with their individual identity?

Value proposition

An exoskeleton as personally tailored and essential your own spectacles.

Project Criteria

Criteria for the product solution has been categorised and implemented based on the Kano Model of customer satisfaction. The method was chosen to provide the team with a more transparent overview of the collected criteria and a way to identify which are must-haves and which are nice-to-haves. The Kano Model has separated the requirements into Performance, Basic and Delighters. Further in the report, the team will utilise this method to collect upcoming criteria in all the explored categories being Function, Application and Aesthetics.

	Performance	Basic	Delighters
All	**C12: Should be aesthetically customizable** **C3: Must be fitted for the home-scenario** **C2: Should provide higher independency** **C9: Should dissociate from hospital/ rehabilitation equipment** **C14: Should enable the user to perform three hand gestures: the grasp, pinch and point.**	**C1: Should be applicable across different genders and age** **C11: Should fully control the movement** **C15: Should be easily implementable into the life routines** **C5: Should be fitted to and account for the wheelchair.** **C13: Must not hinder the user's existing movement capabilities.**	**C10: Should be fitted an individual user identity** **C8: Should be able to be worn under a jacket.** **C7: Should take up minimum space.** **C6: Should be lightweight.** **C4: Should not be removed too often in a day.**
Glove	**C17: The DIP, PIP and MCP joints should bend approximately simultaneously.** **C24: The material needs to be slightly stiffer where the tendon sheaths are placed.** **C16: Should use tendon actuators.** **C26: Should be form fitting.**	**C32: The outer layer needs to be wipeable with disinfectant.**	
Brace			
Liner	**C30: Be machine washable.**	**C27 Should be breathable.** **C28 Should be moisture wicking.** **C29 Should be temperature regulating.**	**C31 Needs to be able to sweat and body oils.**

Specifications

Some criteria defined in the last phase have been specified further into requirement specifications and are collected throughout the process.

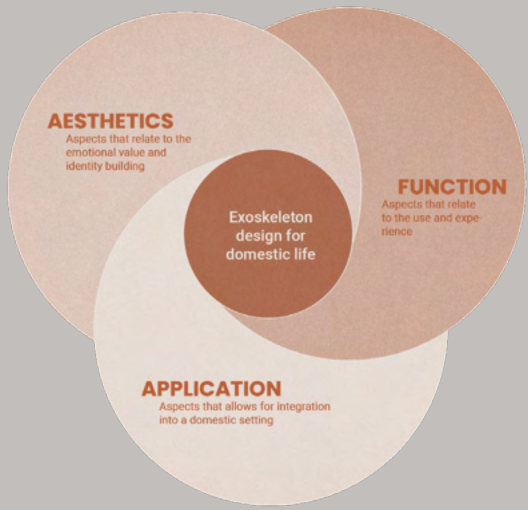
Part	Performance	Metric
Glove	C18: Should provide a passive resting position of 30 degrees in passive mode.	Celcius
	C21: The woven elastic element should be anchored at the DIP joint and edge of the wrist.	Cm
	C23: Tendon sheaths are placed only on the lower side of the finger running along the sides.	N/A
	C25: Should enable speeds in a spectrum between 4,2 cm/s and 2,2 cm/s.	cm/s
	C19: Tendon sheaths are placed as close to the finger as possible.	N/A
Brace	C22: The brace locks the thumb in an 80 degree abducted position.	Celcius
Actua-tion module	C33: The actuation must not exceed 10*15 cm	Cm

Phase reflection

Project overview

Using the working principles from the previous phases, the team has created mōtus. mōtus is an exoskeleton glove that seeks to revolutionise the way humans live with robotics. This is not done by innovating on the mechanical front but rather by prioritising identity while enabling the essential actions. mōtus combines function, application and aesthetics in a holistic solution that encapsulates everyday life.

There are still unresolved aspects of the product that need further attention. These need to be tested, evaluated and iterated if needed to define.

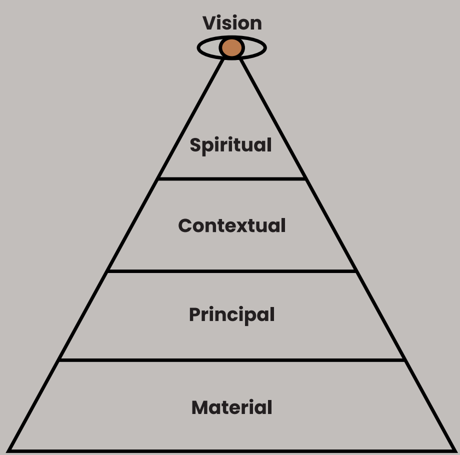


ill. 129. Holistic model

The pyramid model

This phase focused on the contextual, principal and material level. Looking at existing solutions on the exoskeleton market and home medical devices, it was identified which design should be avoided to create the 'right' associations and align with the vision.

Different strategies and aesthetic directions were explored to find an appropriate balance between form and function. Ultimately, having an abundance of customization options weakened the occasion-based narrative. To recreate a strong link between the vision and physical product, the basis of comparison was reevaluated to fit the exoskeleton market. By reducing the customization down to the 'essentials' and focusing on the core of the problem, the final iteration of mōtus attained a stronger connection between the different levels.



ill. 130. (Lerdahl, 2001)

Construction

Phase 6

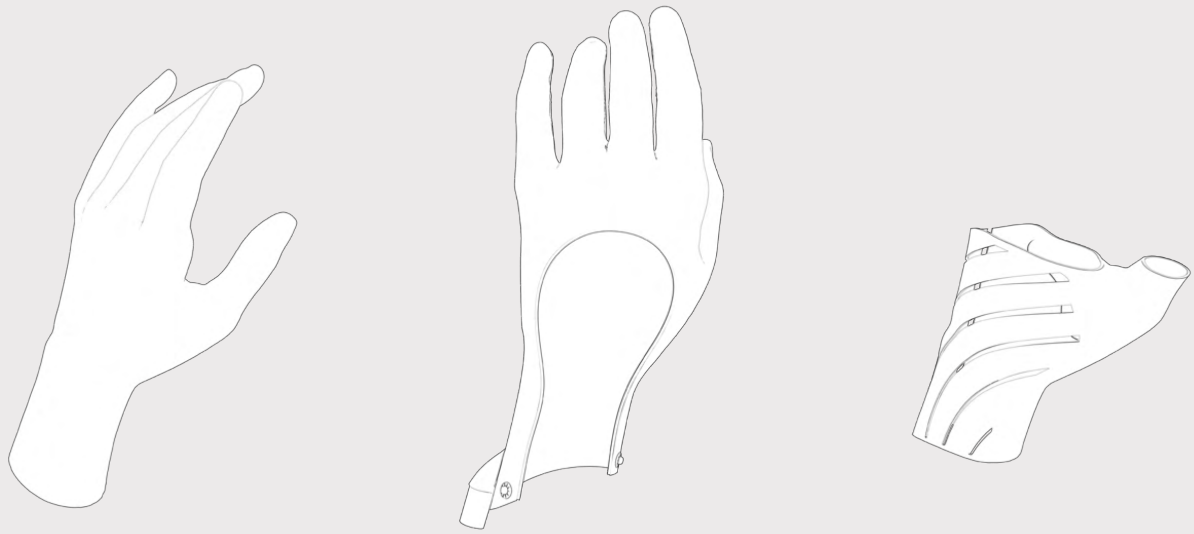
This phase focuses on further specifying the solution space by identifying critical points in the use case and construction using exemplary dives on different components of the product. Mock-ups, testing and expert insights provide the foundation for determining a solution to these considerations. Based on the criteria of all prior phases the appropriate materials properties, components and production methods for mōtus. Mock-ups and analyses are used to compare different considerations and identify synergies between the aforementioned. This all culminates in the final product specifications at this stage in the development.

Product architecture

Introduction

After identifying different problems and solutions in the previous phases, several parts and components have been implemented into construction. This chapter serves to answer the question “Which parts does the product consist of and what purpose do they have?” by presenting the final product architecture.

The product has four primary parts: Glove liner, outer Glove, the Brace and an actuation module. Each of them serve a specific purpose relevant to being integrated into everyday life. In the following, each part, their sub-components and the reasoning for being as they are, is explained.



ill. 131. Liner (left), glove (middle) and brace (right)

Glove liner
The inner layer is primarily a hygiene control. It acts similarly to base layer clothing like socks, wicks off moisture to ensure a dry hand and should be changed after each use. It is chosen to implement the woven bands on the upper of the finger to make it easier to don the outer layer. The inner layer is machine washable to fit into existing washing routines and is not particularly visible when wearing the product.

Glove
The outer layer is the contact surface with the surroundings and contains the tendons on the palm side of the hand. Because the cables connect to the actuation module and can not be detached, it is not machine washable but can be soaked. It can however be wiped with disinfectants. The outer layer is fastened to the brace using buttons.

Brace
The brace is a hard shell that stabilises the wrist and thumb, while putting the thumb in an advantageous position. The brace is closed using a dial lock lacing system. It is specifically fitted to the user to ensure prolonged comfort. The brace should not be machine washed but can easily be wiped or hand washed.

Actuation module
The actuation module is a housing box that contains the motors, battery and microcontroller. The tendon cables in the outer glove are connected to the motors and module through a wire. It is recommended that it is attached somewhere on or near the user.

Construction dives

Relevant dives are made for the construction of the different parts. These dives explore aspects from a mechanical perspective, whose purpose is to ensure the product can function as intended and fulfill the product vision. Five exemplary dives will be made.

Kinematic test of strength
Exploration of the cable routing with added weight to test if the system is strong enough while still keeping the desired movement sequence.

Friction of the Glove
Exploration of how to ensure a secure grip on an item, so the user does not drop it.

Deformation of the brace
Exploring the requirements to the brace to minimize the risk of deformation, fatigue and or breakage over time.

Integrity of the Glove
Exploration of the material properties needed to keep the integrity of the Glove when the product is in use.

Integration of the artificial tendons
Exploration of how to best integrate and attach the artificial tendons to provide the most agile movement.

Kinematic test of strength

Introduction

Previously, different iADL scenarios and actions were identified (see apx. 12). These are looked at again to determine what the heaviest single-handed task could be. The heaviest object that would be lifted with one hand is a large coffee pot or a bag while grocery shopping. The maximum weight is set to 2.2 kg as it fits many large coffee pots or thermos' with liquids (see apx. 22).

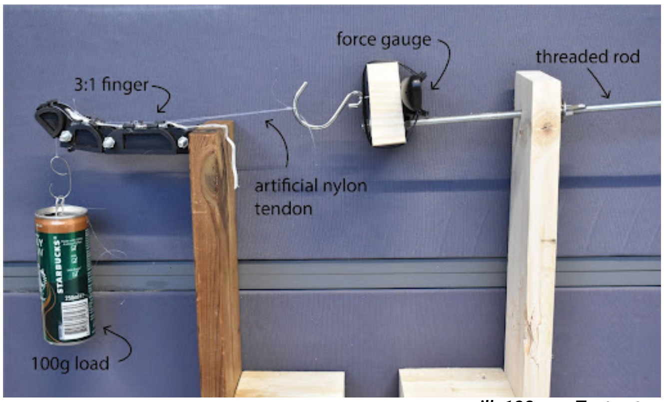
Kinematic test of 3:1 finger

To test the force required, the 3:1 finger mock-up was used. The finger was attached in a setup where the required force in different positions could be measured. This was done to identify the point where the finger would be put under the largest stress as well as examine if the finger still moved as desired when applied a load (see apx. 25).

The finger was tested with the load being attached to the different joints in the finger and one where the weight is distributed. A 100g load was used for all tests.

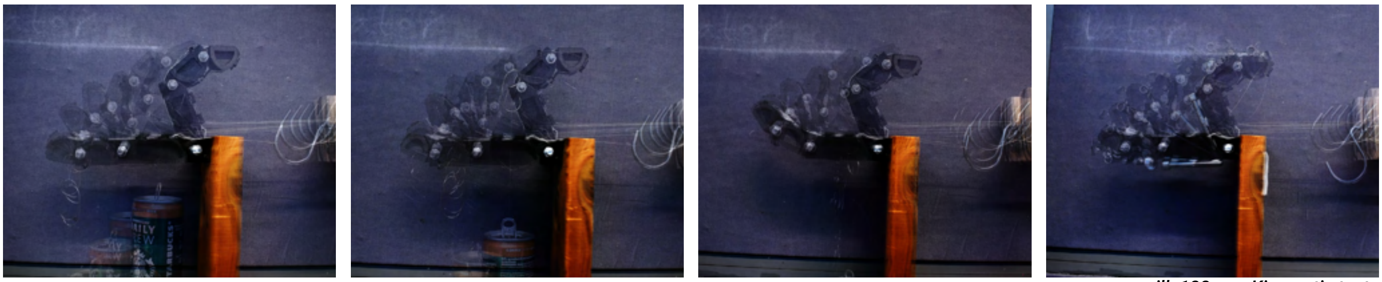
Sources of error

The construction was a bit uneven and the rod was slightly loose, which might have provided unrepresentative results. However, to accommodate this issue, the team took three tests per configuration from which only the resulting mean is presented here.

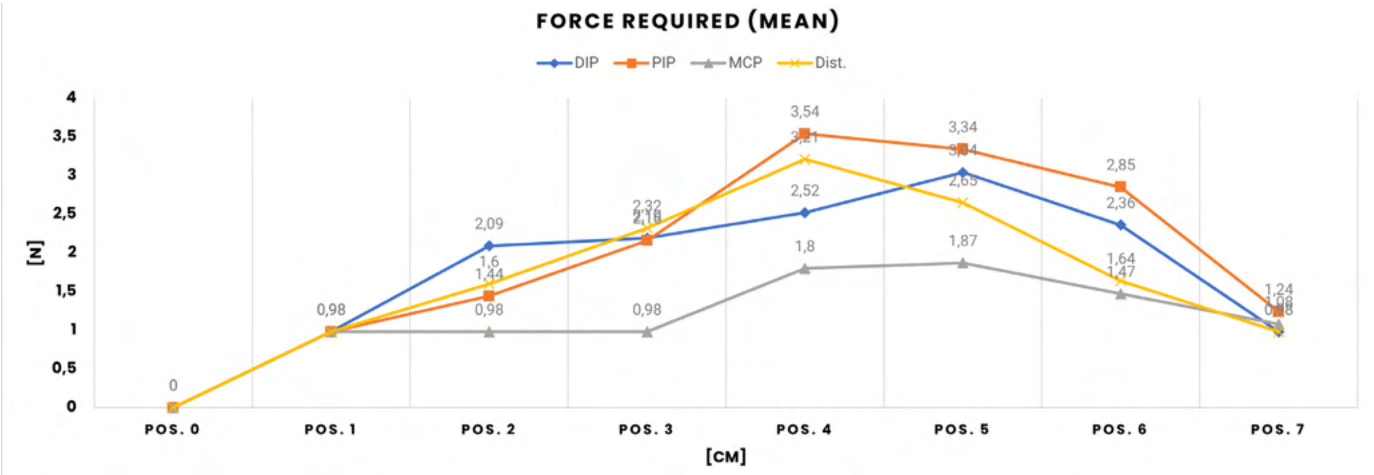


ill. 132. Test setup

DIP. Max force: 3,04 N **PIP. Max force: 3,54 N** **MCP. Max force: 1,87 N** **Distributed. Max force: 3,21 N**



ill. 133. Kinematic tests



ill. 134. Graphic representation of kinematic test

c34: Each motor should be able to produce 15 N of force.

Test results: Validation of the system

To the team's delight, the added weight to the construction did not alter the movement sequence as set in phase 3, as initially feared, which only verified the cable routing and added elastic qualities. The steepest force requirement is 3,54 N. Therefore this number is used to calculate the motor specifications by scaling it up. In addition, to accommodate for the sources of error and make the construction viable beyond the identified load, a factor of safety of 2 is built into the product. Using the identified numbers, a force of approximately 15 N per motor is required.

Test: Surface friction 1 – Lifting objects

In a real life scenario, the user will need to grip different objects that are not necessarily dry or 'grippy'. A quick test is conducted to experience how it feels to lift objects with different surfaces: dry, dusty and wet. Firstly, a smooth cotton glove is used and afterwards a glove with silicone dots.

Dry **Wet** **Dusty**

ill. 135. Friction test on can

c35: Each finger should have a grippy surface.

Test results: Friction when lifting objects

If the grip was sufficient to put the object in equilibrium, there was not any noticeable difference. However, when loosening the grip slightly, the scenarios with water and dust would slip at a quicker rate due to them acting as an extra layer on top of the object. This was especially apparent with the cotton glove. Overall, despite being fingerless, the glove with silicone friction surface made it significantly easier to hold onto the can in all three scenarios. Therefore, it is decided to implement a grippy surface on the palm side.

Reflection: Pressure sensors in the fingertips

During the test, it was easy to judge when there was sufficient grip. However, for individuals that are unable to feel in their fingers, it may be beneficial to implement pressure sensors and a feedback system so they are not reliant on visual feedback and forced to look at the object they want to grip. For a basic version of the product, this is not taken into account at this point, but there should be room for the necessary components for a 'premium' version.

Test: Surface friction 2 – Pushing the wheelchair

A second test is conducted to test how friction affects the wheelchair driving experience. This is done to include more aspects of the everyday context for the users. The brace was worn to limit wrist mobility to better act out how the users would perform this action.

c36: The palm of the brace should have a grippy surface.

ill. 136. Friction test on wheelchair

Test results: Friction when pushing the wheelchair

The users are accustomed to not use their fingers when they push their wheelchair. Rather, they push the wheelchair using only their palms. Even though the product would enable them to perform this action in a different manner, they might want to continue doing it like they are used to. Ultimately, it was much easier to push the wheelchair with the silicone dots as the smooth outer of the cotton glove provided no friction and just slid off the wheel handles. Therefore, a grippy surface on the brace on the palm should be implemented as well.

Conclusion

After reevaluating the previously identified iADL scenarios, a maximum weight of 2.2 kg has been determined for single-handed lifting tasks. To lessen the risk of dropping objects, a factor of safety of 2 should be built into the product. In addition, a grippy surface is implemented on the palm side of the outer layer and the brace to ease everyday tasks such as lifting objects and pushing the wheels on a wheelchair.

Deformation of the brace

Introduction

When evaluating the product, the part that is most affected by stresses is the brace since it prevents the wrist from flexing. To ensure it can withstand daily use, the critical points of it and the deformation risks were explored. The first order of business was to contact a physiotherapist to provide the team with areas to be aware of when designing a brace so as not to put strain on the wearer.

Interview with Physiotherapist Katrine Valentin Christiansen

Katrine is a 24-year old physiotherapist located in Holstebro. She has immense knowledge of the body, not only through her studies and occupation, but also due to her very active lifestyle.

ill. 137. Katrine Valentin Christiansen

After testing with the gauze plaster, it was discovered that a snug fit was necessary for the brace to properly function. To gain insights into what is required to properly stabilise the wrist while providing sufficient comfort, physiotherapist Katrine was contacted. The reasoning for contacting an expert is to get another perspective on the topic than desk-top research would provide. The interview was semi-structured with pre-prepared questions and conducted online (see apx. 20). After explaining the problem space, Katrine was quick to provide pointers to how the brace should be fitted, supported and about the wrist as a whole.

Fitting
Regarding the fit of the brace, these were the primary insights:
- It should provide sufficient stability and not cause pain
- As a rule of thumb, you should comfortably be able to slide one finger between the brace and skin.
- Generally, to be able to close your hand into a fist. If you close your hand gently, the brace should end slightly below where your nails sit.
- The skin is one big organ. Therefore, it needs to be able to breathe

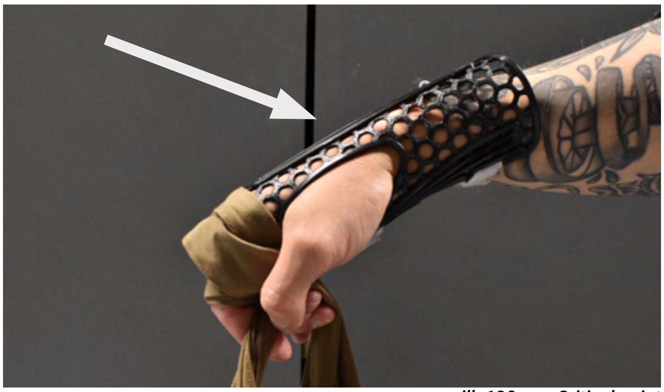
Support
Regarding the supportive aspect, these were the primary insights:
- The main support should be on the flexors and extensors as they have a greater range of motions than the other direction.
- Since the hand and wrist are severely locked into one position, the muscles can not work. This can become a big issue because keeping the joint mobile is quite important for your users. You need to be able to move the muscles just a bit and the material cant be too rigid.

The brace can not be too tight or short as it would injure the wearer.

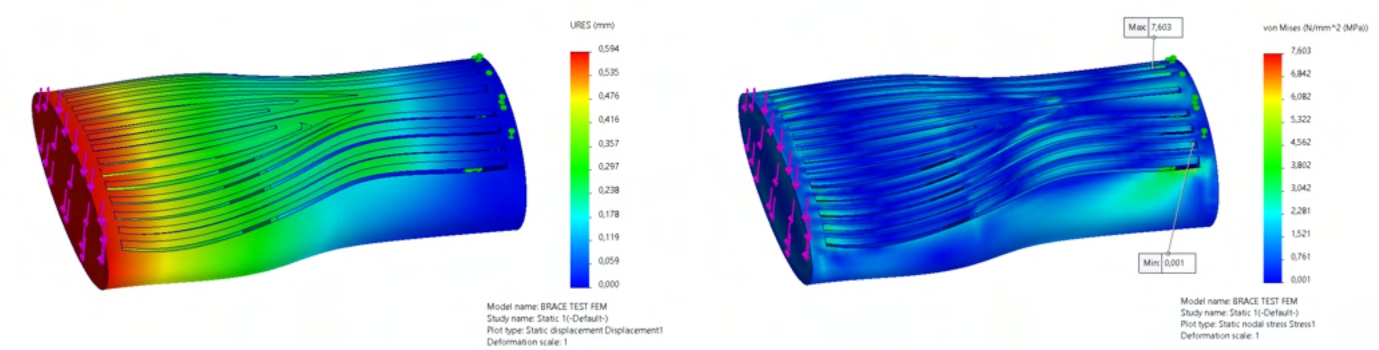
Finite element analysis

Following up on the interview, a finite element analysis was conducted to examine its structural integrity and whether or not there is a need to change the design. The most relevant points in the brace is the force transfer of the flexors and extensor, as well as the ulnar and radial deviation. Simply, when pressure is put on the wrist, it will move in the vertical or horizontal plane.

A simplified CAD model of the brace was constructed as the test element, with a wave pattern cut out. Due to the timeframe it was not possible to construct a hand to add as the support points, so three pillars were added inside the brace to provide structure so that it would not collapse of itself. The test was constructed with both PLA and ABS, but only ABS is shown here.



ill. 138. Critical point



ill. 139. Brace FEM analysis. Left: displacement, Right: stress

Results: Inaccurate measurements

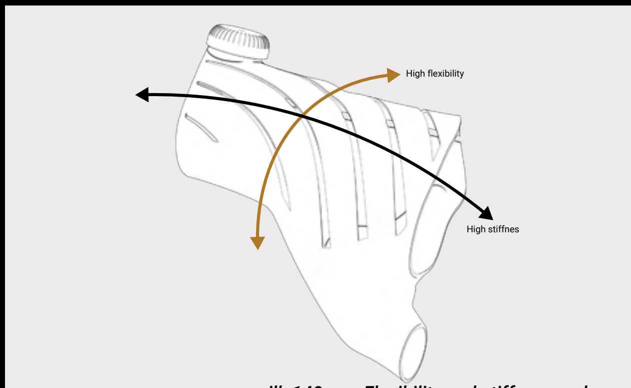
Unfortunately, the teams attempt to replicate the deformations and stress build up, were futile as the results were not true to nature. The deformation scale showed highest deformation in the front of the brace where the load was set, however the deformation was expected to be centred around the wrist joint in the middle of the brace. Because the expected stress concentration was not shown. However, the test did help the team decide on the material choice, which will be ABS, due to its higher strength and ability to be 3D printed. It also highlighted that the biggest stress concentration was placed in the corners around the cutouts. This was as expected since they were sharp-edged and not rounded.

Reflection: Needs further testing

Since the test was not true, it would need further testing. However, it did provide a deeper insight into which factors to account for next time, and which questions to ask. As the hand is an element with both harder and softer parts, each of those needs to be mapped in order to place the correct supports in an FEM analysis. This data would provide the team with a better insight into which parts of the brace would need more and less rigidity. The current assumption as to what we are looking to define is:

A higher flexibility across the brace
This would enable the brace to be bended and opened slightly to make it easier to put on

A higher stiffness along the brace
This would provide support against unintended flexion of the wrist and thereby keep it in place when in use.



ill. 140. Flexibility and stiffness on brace

c37: Should be higher flexibility across the brace.

c38: Should be higher stiffness along the brace.

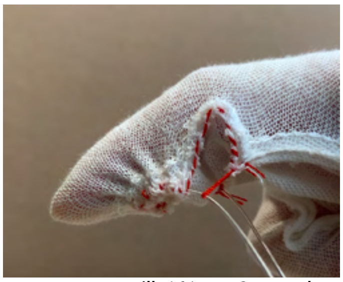
Structural integrity of the outer Glove

Introduction

Previous tests have pointed towards a clash between the construction's ability to stretch and the stiffness required to properly pull the tendon cable. To uncover these, and define the material properties needed for the construction, tests are conducted to investigate the requirements for rigidity and stiffness in the glove.

Mock-up: Soft cotton construction

Using a quickly made mock-up, it became evident that the high flexibility in the material (due to the loose weave structure) made the glove too elastic and thereby making the movement of the finger inaccurate when force is applied in the artificial tendons. The force of the artificial tendons are pulling in the fabric making it increase the distance between the finger and the tendons which affects the movement negatively.



ill. 141. Cotton glove

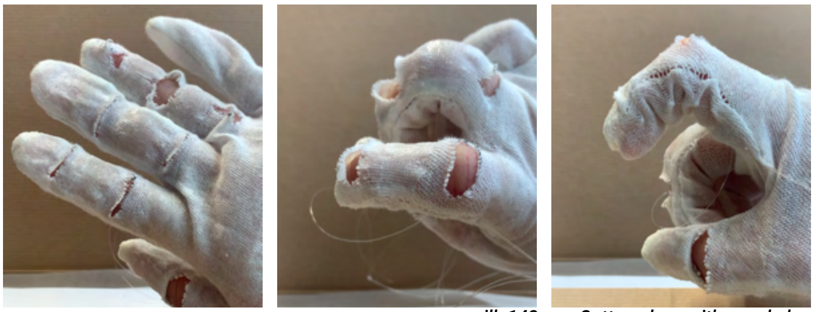
Mock-up: Rubberised work glove

It was observed that the work-gloves used in other mock-ups provided a different stiffness because of the rubber coating on the palm. A mini-study was therefore on this glove to compare the two and how the added stiffness changed the motion and fit of the glove. The glove was flipped around so the stiffness was on the back of the hand and finger, since it was in these areas the former test showed deformation and problems. This mock-up had a higher stiffness all over, which restricted some movement when bending the finger. To solve this, some cutouts were done to the glove to increase some flexibility around the joints. This test showed that the glove held its form much better and the movement of the finger was more lifelike and felt more comfortable.

ill. 142. Work glove

Mock-up: Defining and finalising stiffness and flexibility

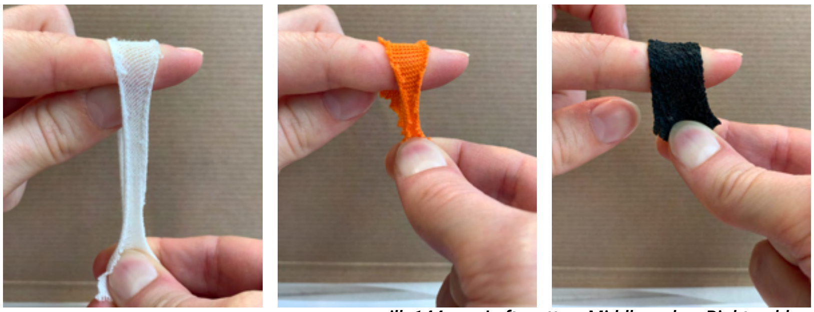
This construction consisted of a cotton glove with wood-glue placed in the areas which needed stiffness and cut open to provide flexibility where this was required. The test showed the mock-up worked as expected by keeping a tight fit and the tendons as close to the finger as possible, and still providing the desired motion. Several cutouts placements were made on different fingers to determine which one created the most comfortable and agile fit.



ill. 143. Cotton glove with wood glue

Test of deformation in different materials

Different materials were tested to get clover to define the material property which could provide the necessary strength and young's modulus to provide sufficient stiffness across the back of the fingers. As rubber showed the least deformation in the material it was chosen as point of reference and the e-module was calculated.



ill. 144. Left: cotton, Middle: nylon, Right: rubber

Deformation of rubber component

The stress and strain of a rubber piece was calculated by testing its deformation under force. The force was deciphered from the force gauge and the cross-sectional area of the piece was measured and calculated. From this we can conclude that the stiffness of the material across the fingers could ideally be around the 2MPa.

Even though the material properties can not be compared with those of woven textiles, this number and test is not definitive, but can serve as an initial indicator of the stiffness needed and thereby be a baseline from which further tests need to be made.

ill. 145. Pull test: rubber

Additional benchmark: deformation of tightly woven cotton

The stress and strain of a rubber piece was calculated by testing its deformation under force. The force was deciphered from the force gauge and the cross-sectional area of the piece was measured and calculated. From this we can conclude that the stiffness of the material across the fingers could ideally be around the 2MPa.

Even though the material properties can not be compared with those of woven textiles, this number and test is not definitive, but can serve as an initial indicator of the stiffness needed and thereby be a baseline from which further tests need to be made.

ill. 146. Pull test: woven cotton

Conclusion

The test highlighted which areas on the fingers need sufficient stiffness and flexibility.

- The part which covers the palm needs higher flexibility for the fingers to curl inwards during the movement.
- The topside however needs a mixture of high stiffness and high flexibility.
- Transverse we need high stiffness.
- Longitudinal we need high flexibility.

An ideal solution would be to choose fibres which would easily return to their initial position after flexion. The weave should be uni-directional. This pattern has the fibres in one direction be aligned and the other direction they are perpendicular. The aligned fibres will have a high stiffness and the perpendicular direction will have flexibility.

This information will be used to determine a possible material match for the outer glove which could guide the production process. This will need further testing with the right materials in future development processes - ideally with assistance from textile designers and engineers.

c39: Needs high stiffness transverse.

c40: Needs high flexibility longitudinal.

Cable attachment

Introduction

During the cable routing exploration, the cables were attached by running through tendon sheath imitated by tubing. However, as the cables are the primary working principle, they should be hidden, unexposed or protected otherwise to reduce the risk of breakage.

Mock-ups: Cable attachment

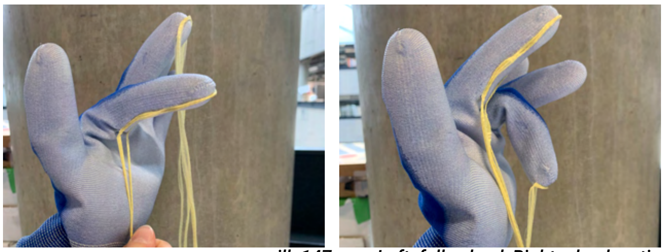
Different attachment principles are mocked up with aramid string, (which has very similar properties as the desired material, Dyneema string), to examine which qualities; functional and aesthetic, are fitting for the solution. While doing this, initial considerations to production were also done. These different methods of attachment are deemed as having potential for exploration:

1. The cable is sewn directly into the glove.
2. The cable is sewn around the finger in a route (made previously).
3. The cable is glued to the sides of the finger.
4. The cable is glued the entire cable routing on the finger.
5. The cable is not looped across the nail area but in two separate parts.
6. The cable runs through a sheath (which was tested previously).

Glue

It was quickly discovered that the finger is not able to bend when the cable is glued below the distal phalange. This was due to the cable not pulling the fingertip but only the MCP and resulting from this, the entire finger. When the cable was pulled with these kinds of configurations, the finger just formed an L-shape.

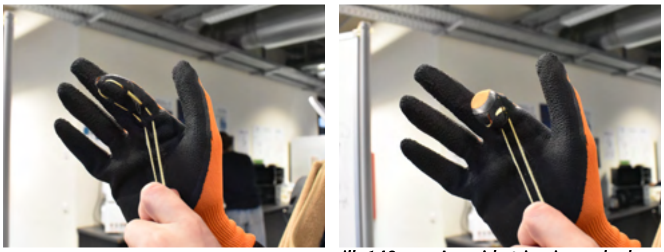
When the cable is only glued to the tip of the finger, it acts more according to the desired motion. However, it still requires a “track” along the sides of the finger to bend it as desired.



ill. 147. Left: fully glued, Right: glued on tip

Sewn

When the cable is sewn directly into the glove, it behaves exactly as desired. Going this route, however, requires that there is very low friction between cable and material as experienced when testing on different materials: one being smooth cotton and the other being rubberized polyester. The cable moved seamlessly in the cotton and got stuck quickly in the rubberized polyester.



ill. 148. Aramid string in work glove

Sewn route

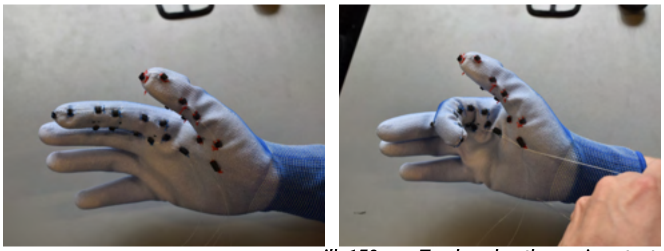
The finger moves as desired. Again, for this principle to work to a sufficient degree, there can not be much friction between cable and glove, as it will get stuck. This makes production quite simple as the cable will be sewn onto the glove after assembling it. However, it leaves a visible mark that indicates where the cable runs.

ill. 149. Nylon string in work glove

Tendon sheaths

Previously, a mock-up was made where the cable runs through tubes imitating tendon sheath. This provided the desired motion but it is unsure whether the construction of the final product will be difficult to construct using this principle.

An alternative to avoid having the cable running over the fingertip is to ‘cut’ the cable in two and make it stop at the distal phalange. It provided the desired motion but like the previous iteration (tendon sheaths) it is unknown whether or not this will be difficult to construct.



ill. 150. Tendon sheath: previous test.

Conclusion

It is decided to pursue the principle in which the cable is sewn around the glove finger. To reduce friction, the cable will run through a long tendon sheath. By taking this approach, the overall aesthetic is also affected, making it look more clothing-like with the ultra visible stitching. The stichting should not only draw association to clothing but also tell the user about the functionality of the product, i.e. where the tendons run.

c41: The artificial tendons should be sewn into the Glove.

Product sizing

Introduction

The brace is essential for the product to function properly. Therefore, this part will be 3D printed to provide the needed support and comfort. However, the sizing options for the glove component itself does not need to be as intricate. Using standardised sizing guides, a size spectrum is created that will fit nearly all individuals.

Sizing chart

The brace is essential for the product to function properly. Therefore, this part will be 3D printed to provide the needed support and comfort. However, the sizing options for the glove component itself does not need to be as intricate. Using standardised sizing guides, a size spectrum is created that will fit nearly all individuals (see apx. 27).

It is decided that the kick-start of mōtus will start with only six of the twelve glove sizes possible to minimise the initial production cost but still represent a broader size spectrum which would target a healthy sum of potential users. As hand sizes can vary across ages and genders, the spectrum will be unisex. The circumference is based on the paris inch inspired by the spectrum provided in Rhanders gloves and the hand length is based on Digitx lengths.

mōtus UNISEX sizing chart						
hand circumference (cm)	**16 - 17,5**	**18,5 - 20**	**21,5 - 23**	**24 - 25,5**	**27 - 28,5**	**29 - 30,5**
hand length (cm)	**16 - 17**	**17 - 18**	**18 - 19**	**19 - 20**	**20 - 21**	**21 - 22**

Conclusion

These initial sizes will fit most people, without accounting for the 1⁄2-sizes. Customers who find themselves in between the intervals of hand circumference could be either of the two sizes (possibly a 1⁄2-size in between) and their final fit would be based on their hand length.

Materials and production

Introduction

Using identified insights and criteria, different materials are evaluated. The focus lies primarily with the functional and applicable areas of the holistic view. It should be noted, however, that if the material does not allow for the customization options determined in phase 06 – aesthetics, it will not be considered in the first place (see apx. 26 and 30). In addition, the essential components are found for the actuation module, and the intended production method is described.

Glove liner – Bamboo rayon

The inner layer is the layer that is in contact with the skin. Therefore, this part of the glove should provide a particularly high comfort level for its wearer. It is extremely important that this material is machine washable without detrimental side effects. Breathability, washability, moisture wicking and softness are prioritised criteria for this material to ensure prolonged comfort and ease of use (cleaning, machine washable). Stretch also helps ensure a better fit without causing discomfort. **For these reasons, bamboo rayon is chosen as the material for the inner layer.**

The glove liner will be produced using a circular knitting machine. This enables the elastics to be knitted into the structure of the liner. This production process will be outsourced.

Outer glove - COOLMAX

The outer layer is the layer in contact with the surrounding environment. As this material is not directly in contact with the skin, the focus is on a material that can provide a greater degree of protection while still allowing for comfort. Most importantly, the material needs to be durable to protect the inner layer and avoid getting quickly worn out. It needs to be breathable, moisture wicking and easily maintained and cleaned (wipeable). Lastly, it needs to be able to be produced in a way that allows for stiffness across the finger and elasticity along the finger (pp. 70). **Given this, a synthetic polyester blend, COOLMAX, is chosen.**

Like the glove liner, the outer glove will also be produced using a circular knitting machine. As the machine creates a knitted structure consisting of interlocking yarn loops, the yarns are not locked in one direction but change continuously. Simply, this means that it can create thinner meshes where elasticity is needed and tight weaves in areas where stiffness is required. The tendon sheath and cables will afterwards be sewn manually onto the product. In addition, the product would have no visible seams due to the machine not making cuts but comparatively building a weave from scratch, similarly to 3D printing (Chinahanma, 2021). Initially, the machinery is outsourced to a sub-supplier due to the machine's steep price and complexity of working the circular knitting machines.

Brace - ABS plastic

The brace can have two functions; firstly, if the individual needs support it has to be rigid enough to stabilise wrist and thumb. Besides stabilisation, being able to mould the material to the user's hand and wrist without exceedingly high costs is equally important. Because this part requires an incredible individualised fitting, a material that is able to be 3D printed is chosen. To meet the demands for highly personalised fits, 3Dscanning the wrist and 3D printing it is chosen as the production method of choice (Hubs, 2023). **Because of these considerations, ABS is chosen as the material for the brace.**

Lock dial lace

To tighten the brace, a dial lock is used. This mechanism shows clear affordance and is usable with only one hand. This component will be sourced from a manufacturer. Furthermore it can be easily replaced should it break.

Actuation module: ABS plastic

As mentioned previously, the actuation module has not been prioritised as highly as the glove component of mōtus. However, using the identified specifications to the components as well as benchmarking principles from existing products, some initial considerations have been made to the component types. The housing itself will be 3D printed in ABS during the initial series 0 launch with the expectation to be injection moulded when the business is profitable enough.

Cable

It was identified previously that the cable needs to act similarly to tendons in the human hand. In addition, the cables only need to act on an unidirectional pull of approximately 15 N as the passive extension will open the hand back up. Benchmarking from the current state of the art of exoskeletons, and the aramid-test (pp. 71) Dyneema string is chosen for the cables due to its high strength relative to size, low friction, flexibility and low weight. To aid with reducing the friction, a teflon tube is used as the sheath (Pitzalis et al., 2023). The Dyneema string will be bound and glued with a strong adhesive to a pin at the end of the motor. Through a test with aramid string, with almost the same properties, this solution was verified.

Motor

To enable the three hand gestures, the product needs three separate motors. One controlling the thumb, one controlling the pointer and one controlling the middle, ring and pinky finger respectively. Each motor needs to be able to pull approximately 15 N. It should be noted that to attain their desired strengths while minimising required space, a costume motor would need to be made. To acquire sufficient force and speed while keeping the construction compact, a DC motor with integrated gearing is deemed as the most appropriate for the product. A potential manufacturer could be Precision Microdrivers Ltd.

Battery

The primary requirement for the battery is that it enables the product (motors) to function for a day cycle of 8 hours. Besides this, the battery also needs to be rechargeable. All this while keeping as compact a size as possible.
An optimal configuration would allow the battery to detach from the rest of the actuation module. Here, the user could be provided with two battery units and switch when one is depleted of power. Benchmarking from existing solutions, a battery pack using Li-polymer batteries is chosen.

Microcontroller and motor controller

Tying every component together and for the product to communicate to the control interface, a PCB is essential. Here, a motor controller for each motor is also needed to control the speed. The motor controller also needs to be able to control direction as the spool should return to its starting position upon release of a given hand gesture.

Design brief 5

Problem statement

How can the design of an exoskeleton-hand be optimised to fit into daily life by enabling tetraplegics to independently participate in social activities and provide a personalised experience that aligns with their individual identity?

Value proposition

An exoskeleton as personally tailored and essential your own spectacles.

Project Criteria

Criteria for the product solution has been categorised and implemented based on the Kano Model of customer satisfaction. The method was chosen to provide the team with a more transparent overview of the collected criteria and a way to identify which are must-haves and which are nice-to-haves. The Kano Model has separated the requirements into Performance, Basic and Delighters. Further in the report, the team will utilise this method to collect upcoming criteria in all the explored categories being Function, Application and Aesthetics.

	Performance	Basic	Delighters
All	C12: Should be aesthetically customizable C3: Must be fitted for the home-scenario C2: Should provide higher independency C9: Should dissociate from hospital/ rehabilitation equipment C14: Should enable the user to perform three hand gestures: the grasp, pinch and point.	C1: Should be applicable across different genders and age C11: Should fully control the movement C15: Should be easily implementable into the life routines C5: Should be fitted to and account for the wheelchair. C13: Must not hinder the user's existing movement capabilities.	C10: Should be fitted an individual user identity C8: Should be able to be worn under a jacket. C7: Should take up minimum space. C6: Should be lightweight. C4: Should not be removed too often in a day.
Glove	C17: The DIP, PIP and MCP joints should bend approximately simultaneously. C24: The material needs to be slightly stiffer where the tendon sheaths are placed. C16: Should use tendon actuators. C26: Should be form fitting. C41: The artificial tendons should be sewn into the Glove	C32: The outer layer needs to be wipeable with disinfectant. C35 should have a grippy surface.	
Brace		C36 should have a grippy surface:	
Liner	C30: Be machine washable.	C27 Should be breathable. C28 Should be moisture wicking. C29 Should be temperature regulating.	C31 Needs to be able to sweat and body oils.

Specifications

Some criteria defined in the last phase have been specified further into requirement specifications and are collected throughout the process.

Part	Performance	Metric
Glove	**C18: Should provide a passive resting position of 30 degrees in passive mode.**	**Celcius**
	C21: The woven elastic element should be anchored at the DIP joint and edge of the wrist.	**Cm**
	C23: Tendon sheaths are placed only on the lower side of the finger running along the sides.	**N/A**
	C25: Should enable speeds in a spectrum between 4,2 cm/s and 2,2 cm/s.	**cm/s**
	C19: Tendon sheaths are placed as close to the finger as possible.	**N/A**
	C39 Needs high stiffness transverse	**MPA**
	C40 Needs high flexibility longitudinal	**MPA**
Brace	**C22 The brace locks the thumb in an 80 degree abducted position**	**Celcius**
	C37 Should be higher flexibility across the brace.	**MPa**
	C38 hould be higher stiffness along the brace.	**MPa**
Actua-tion module	**C33: The actuation must not exceed 10*15 cm**	**Cm**
	C34 Motor force of 15 N	**N**

Phase reflection

Project overview

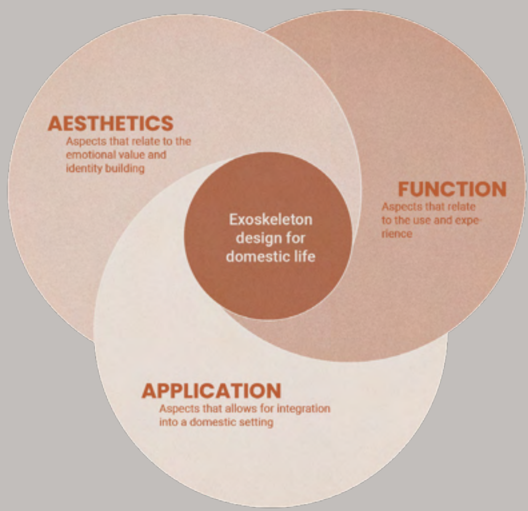
After deciding on a visual identity that connected the three holistic areas, there were still aspects left unsolved. These were especially concerned with the product's construction and which critical points could arise. Most significantly, it was validated that the product could still function as intended while handling weight.

During this phase, the objective was to validate hypotheses and uncover unknowns. To accomplish this task, the team primarily sought to create and test mock-ups, as well as acting out to simulate the user group. Using previous knowledge from reflection in action, the mock-ups were specifically made to reduce sources of error from previous tests.

As the project had taken a user-centered design approach (expert mindset) due to difficulties reaching the users, expert knowledge was implemented to factually validate findings (Sanders & Stappers, 2008). Here a physiotherapist was introduced to comment on the brace.

With these critical points being investigated and resolved, the materials, components and production methods were also decided using the identified criteria.

The final step for the project development is to investigate the implementation and scaling possibilities for mōtus.



ill. 151. Holistic model

Market & Implementation

Phase 7

This phase revolves around the market and implementation plan for motus. The challenges related to the three holistic areas have been sufficiently developed and synthesised in a product proposal. Now, it will be explored how motus will be launched onto the market, its scope and the scaling possibilities. To this, the cost will be calculated in relation to different production strategies.

Market scope

Introduction

Following the development of the product, the focus was to explore the market scope and potentials within. This was done to get an understanding of the sales possibilities and determine the production size for the launch. Furthermore, research was done on competitors with similar products to explore the positioning both in terms of value and cost.

Tetraplegics: The market potential

Incomplete tetraplegics are one of the main target groups for motus, and have been the main focus in the thesis. The injury is unfortunately common all over the world, and in Denmark there are 150 new cases counted each year (Rigshospitalet, 2023). Today there are approximately 4000 (RYK, 2023) danes with SCI, and about 80% of those are cases of incomplete tetraplegia (Uab, 2023). That makes 3200 current individuals in Denmark. Since the target group is based on an injury, there will always be a demand for assistive devices to improve their life quality and enhance their new living situation.

At first glance, this number makes up a relatively small market size, but nonetheless is an inevitable group, who typically has no chances of full recovery like with other similar injuries. Furthermore, the frequency of SCI is not likely to decrease in the future but rather stay consistent, since operating on or trying to fix the spinal cord has high risks. In the interview with Lars Tougaard he also brought attention to the risks and his reluctance to accept further surgery in his hands to increase mobility.

After my operation [to regain a small wrist flexion] the hand-surgeon was very satisfied with the result, but I thought to myself: "Is that it?" I imagined that I would be able to do more.

Including Scandinavia

The initial market strategy would be to market the product towards Scandinavia for a start. The countries of Scandinavia; Sweden, Norway and Denmark, have similar public health systems and economies and thereby have similar resources available to introduce motus on their markets (Moschovou et al., 2022).

Furthermore Scandinavia has a similar design culture, social culture and living situations which might make the market more receptive to the proposal with a Scandinavian design. Furthermore Scandinavia has the Nordic Spinal Cord Injury registry (NoSCoS), which was established to improve care and design of future prevention measures and the care of SCI-centers (Nordicscir, 2023), who might be interested in a product that rephrases the use of wearable robotics in daily life.

Currently there are roughly 14.000 cases of SCI in Scandinavia and 11.200 is expected to be incomplete tetraplegia with collected 450 new cases each year. The first product launch will be targeted at individuals with incomplete tetraplegia.

Sweden	Norway	Denmark
4000 current individuals **~240 new cases each year**	**4000 current individuals** **~95 new cases each year**	**3000 current individuals** **~95 new cases each year**

11.200 **incomplete tetraplegics in Scandinavia**	**450** **new cases each year**

Information from (Mattias Hill, 2021; helsenorge.no, 2016; Rigshospitalet, 2023; RYKb, 2023)

Conclusion

The incomplete tetraplegics will be the strongest target group for the first product launch, since the victims of citizens with similar mobility issues, caused by stroke and nerve damage, have a higher rate of recovery and thereby might not have need of the product long-term. The level of injury and the limitations of each user vary a lot, since it is dependent on the specific injury and the following consequences. This makes it hard to specify an accurate market size, because the product might not be the optimal choice in all cases. This knowledge however, validates making a modular product platform.

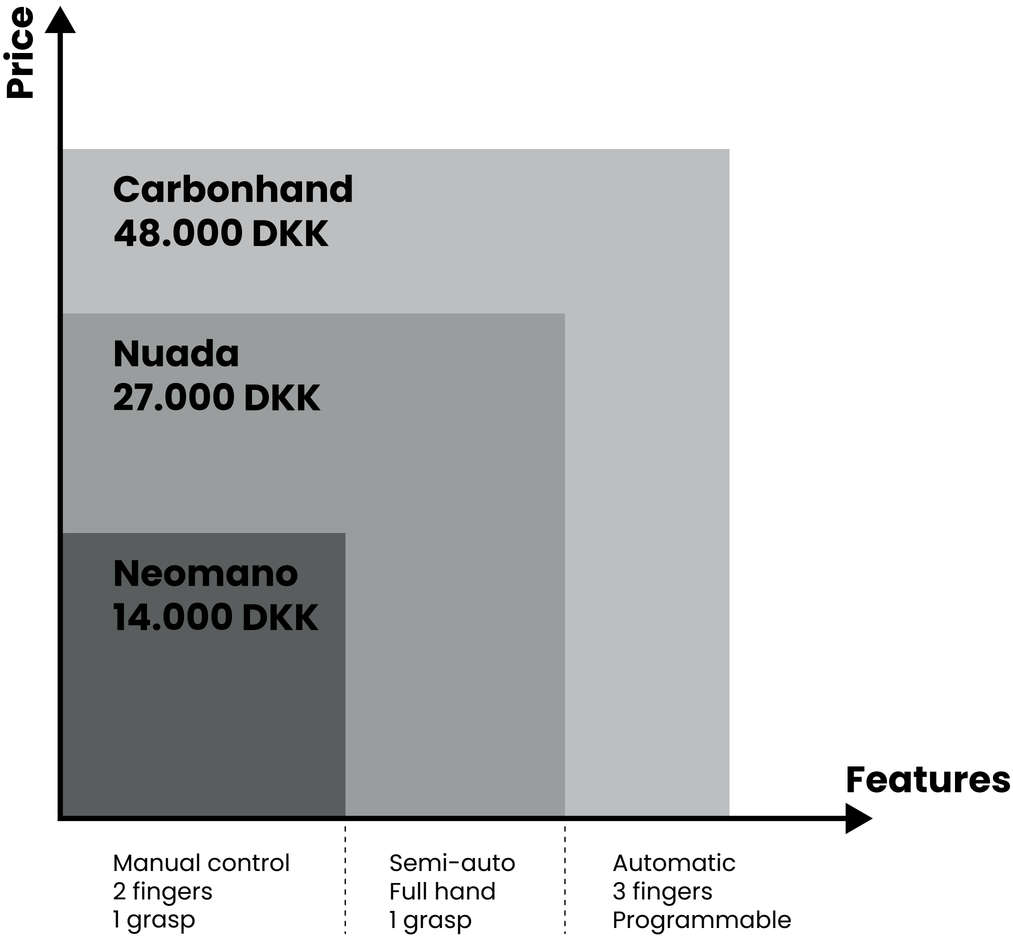
Market innovation level

Introduction

The team investigated the current market of exoskeleton hands to explore the specific innovation motus could bring to the market and which gap to fill. Furthermore, in order not to place the product way off on the market and ensure a strong positioning and even competitive advantage, the price point and market segment was analysed. The team was only able to find three "competitors", with additional products still in development and therefore without price.

Level of innovation

The price point varies approx. 30.000 DKK depending on the number of side applications, materials used and the programmability. This indicates that the market price to match will be dependent on the specific features of the final proposal. Furthermore this highlights that, in terms of costs in production, the electronic components and the development of complex software is one of the major expenditures. With this insight the prospect of vertical scaling was considered, to acquire a strong market hold on more segment levels, and how the cost/value aspect will be influenced if more features are added.

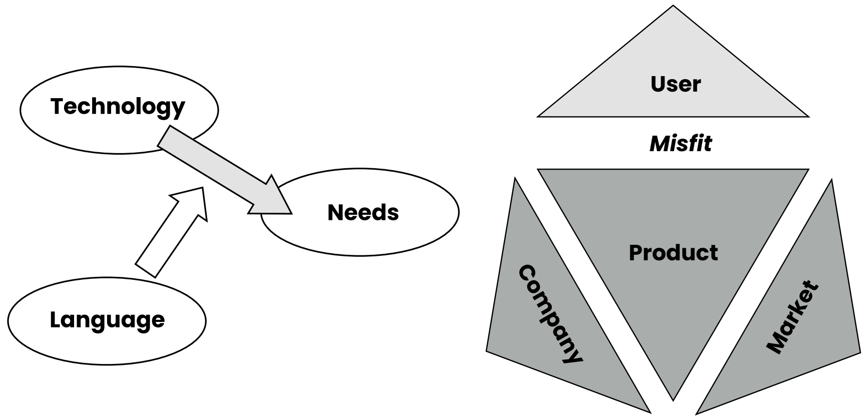


ill. 152. Level of innovation

Highly noticeable is that none of the above mentioned exoskeletons are designed for incomplete tetraplegics or SCI in general, but are targeted at other groups like stroke, fatigue or orthosis. This already places the motus in a blue ocean market, with a yet untouched user segment.

Strategic fit analysis: Existing market

The market fit of existing exoskeletons has been analysed by utilising the three design views by Verganti (Verganti, R., 2010) and the strategic fit models from Haase & Laursen (Haase, L. & Laursen, L., 2023) to understand the shortcomings and define which challenges to overcome. Most exoskeletons on the market today have sprung from a technology push (Verganti, R., 2010). The few years on the market has already proved the potential of the technology and fit to the users functional needs. However we still see product abandonment and exoskeletons ending in the "valley of death" after a while. This is an indicator that the right product language is not yet found, and there is therefore a product-user misfit.



ill. 153. (Verganti, R., 2010)

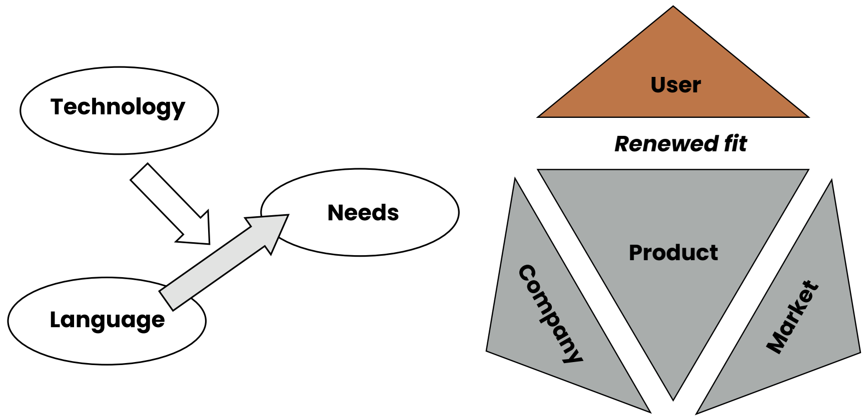
Only functional needs
Because of the technological design view, only the functional needs are covered, losing sight of the interpretability and emotional aspects, which the product design reflects.

The language is off
The current language and narrative of living with wearable robotics are told in the themes: Rehabilitation, Disability, Weakness, which is not in conformity with the users desired self-image

Strategic fit analysis: motus

This thesis project is making a renewed product-user fit by a different design approach.

The strategy is to make a design push, which implements a known language from the self perception and options when wearing clothing and accessories and applying it to the action of wearing robotics. This is to redefine the narrative around using assistive devices to something more relatable and fitting of the context of using it daily. This creates a radical innovation and change on the fit which will need to be tested on the market through user feedback-loops.



ill. 154. (Verganti, R., 2010)

Uncovered market
motus targets incomplete tetraplegics, which currently, no other product on the market does. This gives a market advantage, in a blue ocean market.

"Like wearing shoes"
The language and narrative is rewritten to associate daily living and the norm of wearing shoes. This normalises the use of robotics and distances from the disability.

Individuality
Customizability and the option to personalise the product increases the emotional value and strengthens the relation to the product. motus is also tailored and fitted to the user's hand, which further give that feeling of the product being an extension of you.

Conclusion

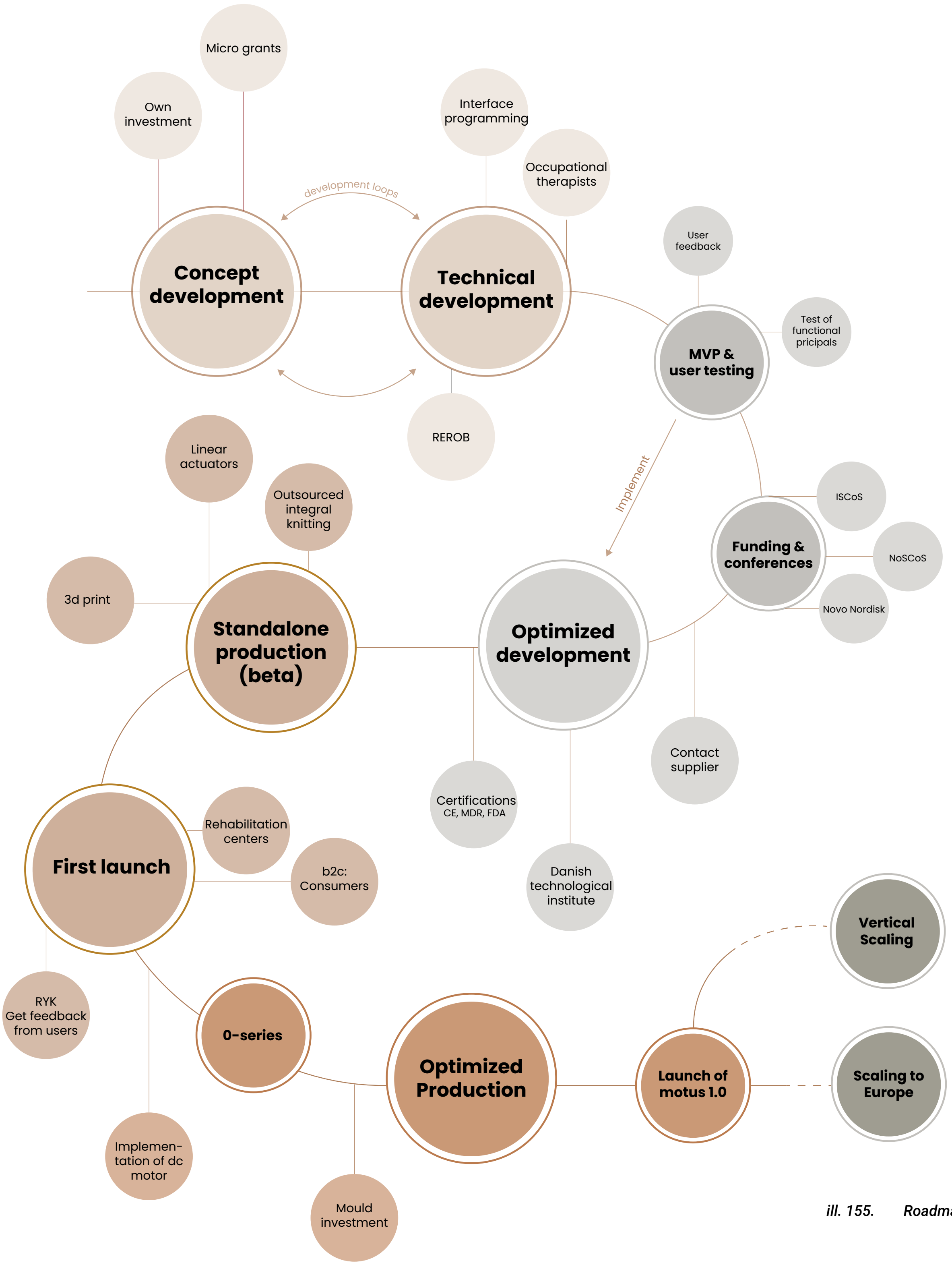
In order to renew the product-user fit the proposal adds additional value through increasing individuality, a clothing narrative and approaching a blue ocean market, through a design push. The strategy applies a language to the product which gives a different meaning to using the exoskeleton with the purpose to normalise the perception of it. By defining the strategic fits and the design view, different ways to approach the market can now be explored and a proposed roadmap.

Roadmap

Introduction

The entrepreneurial implementation strategy of an exoskeleton glove will be a long process and involve thorough technical and functional development in collaboration with expert stakeholders. From the exotic project, the team has gotten some insight into the development process and the timeframe from idea to prototype and onto final product.

The following roadmap illustrates a draft of such a process for this product proposal, which entails four primary phases: Early development, Prototyping and branding, First launch and Second launch.



ill. 155. Roadmap to market

Early development

This phase entails the development of the design, comfort and fit further into depth. This will involve feedback loops from users and test subjects to ensure the material-comfort and the expected fit of the 3d print is as expected. Additional mock-ups and analoge prototypes will be developed for the purpose and used in a build-learn-measure approach (Rries, E., 2011). To sponsor this development the team will seek microgrants and invest themselves in the project to cover material and wages involved.

Furthermore the design will need a throurough technical development, for which the team will use the bird-in-hand principle (Sarasvathy, S., 2008) and team up with REROB to establish a collaborative relationship. They would assist with the development of the software, hardware and interface. By utilising further expert stakeholders in both robotic engineering and physiology in the project would provide the expertise the current design team is lacking.

The development phase is expected to take 3-5 years, depending on the technical difficulties met, and the purpose will be to develop a MVP.

Prototyping and branding

From the development phase the MVP is constructed with just the minimum requirements fulfilled, so it can be used for user testing. For the MVP the actuation method will be via linear actuators, which are easy to source and implement and both gloves will be hand-sewn locally. This phase will use the MVP to test the functionality of the glove on test subjects to acquire feedback and identify areas of error or need for optimization.

This period will also be used to spread awareness of the project and spark interest from potential users and investors. This is done by attending conferences and applying for additional funding for further development. Fonds like Novo Nordisk and NoSCoS are known for supporting similar projects. The product will then undergo an optimization process where the manufacturing techniques will be established to make the design production ready.

First launch

First launch will target 1% of the market to test out and get a first-mover response, which will help determine the product value and whether or not it is a market-fit. Since this launch only produces 100 units, it will be executed in a stand-alone production. Because of the small unit count, reducing cost is a main interest for this process. Therefore compromises have been made to the design and components needed, with inspiration from the MVP.:

- The DC motors will be replaced with linear actuators, which are cheaper, easy to source and implement.
- The housing of the actuation module will be 3D printed and assembled in house.
- The two gloves will be hand sewn in house, since outsourcing for integral knitting might be expensive in machine cost and programming.

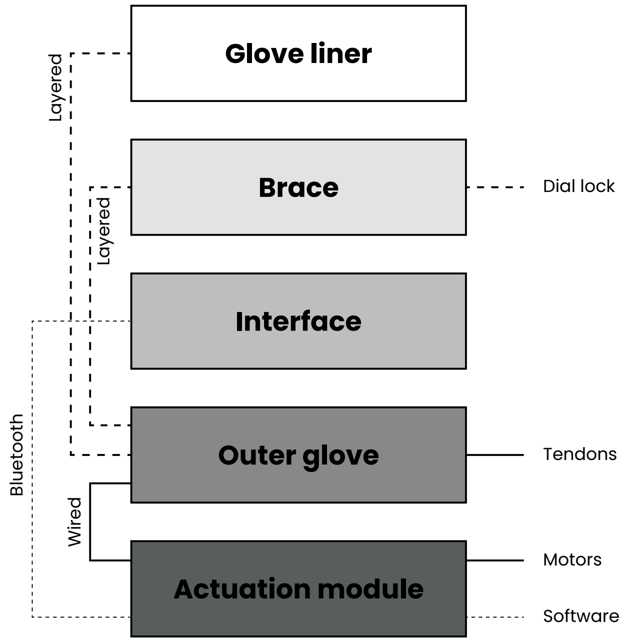
The products of the first launch will be targeted at the first-mover consumers and early adapters. An assumption, based on the user interviews, is that by introducing it to the rehabilitation centres in Scandinavia, motus would make a strong market entrance. It is expected that this group will include the newly injured tetraplegics staying there to learn managing daily living in their current situation, and adapt to new assistive devices.

Secondly, the launch will target the current consumer market and the innovators who are interested in a beta version. The community at RYK will be a valuable entry to the consumer segment, who have yearly meet ups and conventions at Egmont Højskole, where the product could be presented. The overall point of this first launch is to build credibility and trust in the brand, and collect success stories.

Second launch

Based on the market response of the first launch the second optimization phase will be initiated to produce the product as intended. By learning from errors of the first production line, the second can be optimised accordingly for a larger portion of the market. This launch entails the investment of moulds for injection moulding the actuation module housing and developing and implementing custom made DC motors, which will make the module smaller to fit better on the arm. The integral knitting pattern will have developed as well, with the proper technique to make custom glove sizes based on 3d scans. Combined this will strengthen the value of the product and make it seem tailored for the user as an extension of themselves. The sales channels to the consumer market will be strengthened to order from the webpage.

The architecture for motus will be as follows.



ill. 156. Product architecture

Conclusion

Based on this plan of action the team needs to explore the required investments and costs in an implementation with two launches.

Cost

Introduction

A cost estimation has been made to evaluate what the proposal offers in relation to competitive products on the market. The estimation involves pricing for materials, tooling, salaries and other relevant parameters. The cost estimation includes two production setups fitting with what is known on the market.

The market entry for motus will only target 1% of the market and therefore be in a stand-alone production locally without major investments. This lowers the risks involved if the product should be poorly received on the market. This cost estimation is based on a production and sales number of 100 units, and will be used to push a proof of concept to the market and get a first-mover response.

Given the estimated sales number is reached and the market has received motus positively, the second product setup can be initiated. The second setup is an optimised version, where all components and production processes are as intended with some being custom for the product. This launch will strive to cover the whole market, but in production only aim to cover 10% at first, which is about 1100 units.

In the optimised production a higher number of units are produced and most manufacturing outsourced to Asia, which lowers the overall cost per unit. However, since the optimised production implements the custom made DC motors the overall cost per unit is slightly higher.

***Interface**
The 5000 DKK for the interface is an assumption of the price of this, not yet developed, advanced technology.

Standalone production		
Part #	**Part name**	**Variable unit cost**
1	Glove liner	201,90 DKK
2	Outer glove	816,04 DKK
3	Brace	615,50 DKK
4	Actuation module *(linear actuators)*	4174,11 DKK
5	*Interface	5000 DKK
6	Fixed cost	80 DKK
	Total cost	**10.888,55 DKK**

Optimised production		
Part #	**Part name**	**Variable unit cost**
1	Glove liner	3,30 DKK
2	Outer glove	76,64 DKK
3	Brace	446,50 DKK
4	Actuation module *(DC motor setup)*	7278,83 DKK
5	*Interface	5000 DKK
6	Fixed cost	27,65 DKK
	Total cost	**13.171 DKK**

13.171 DKK	22.000	2.000.000 DKK
Optimised production	**Sales price**	**Initial start-up investment**

Conclusion

From the calculations it is evident that the electronic components are the heavy load, as expected. The implementation of DC motors added about 2.400 DKK to the product cost in the optimised production. The actuation module containing these components therefore has the highest variable cost. The two gloves have the lowest cost, which makes it possible to produce and sell a high number of additional gloves to customers for a low price and increase the profit. The product price is estimated to be 22.000 DKK, which is the lower end compared to similar exoskeletons, but with the added value regarding self-image and customisation possibilities.

Reflection: Cost vs. Value

Because of the smaller market size it is considered whether the optimised production will bring the desired extra value to the product, especially in regards to injection moulding the module housing and customised DC motors. The aim was to make a better automated production form and decrease the size of the actuation module, however the experienced user value added is still unclear at this point, to determine whether the investment would be worth it. This will therefore need further exploration in a continued development process.

Verification: Municipalities and subsidy approval

A short casual phone interview with a representative from the municipalities in Denmark, confirmed that the product, at the set price, would be approved as a subsidised aid. It is therefore expected that the customer will be able to get a subsidy percentage for the product in compensation, which would lower the price.

"I am quite certain your product can be approved for subsidy. However, the specific number is dependent on the individual case as well as the assets and specific disability level of the citizen."
Astrid, economist in the health sector, Municipality of Vejle

Increasing the independence of the individual citizen is something that benefits a stakeholder such as the municipalities since it might reduce the number of work hours of a government paid caretaker. The vision could be that the product could have a positive effect on the citizens, which would even motivate them to go to the job market, participate more in society, and increase their overall happiness because of the new found independence.

Breakeven

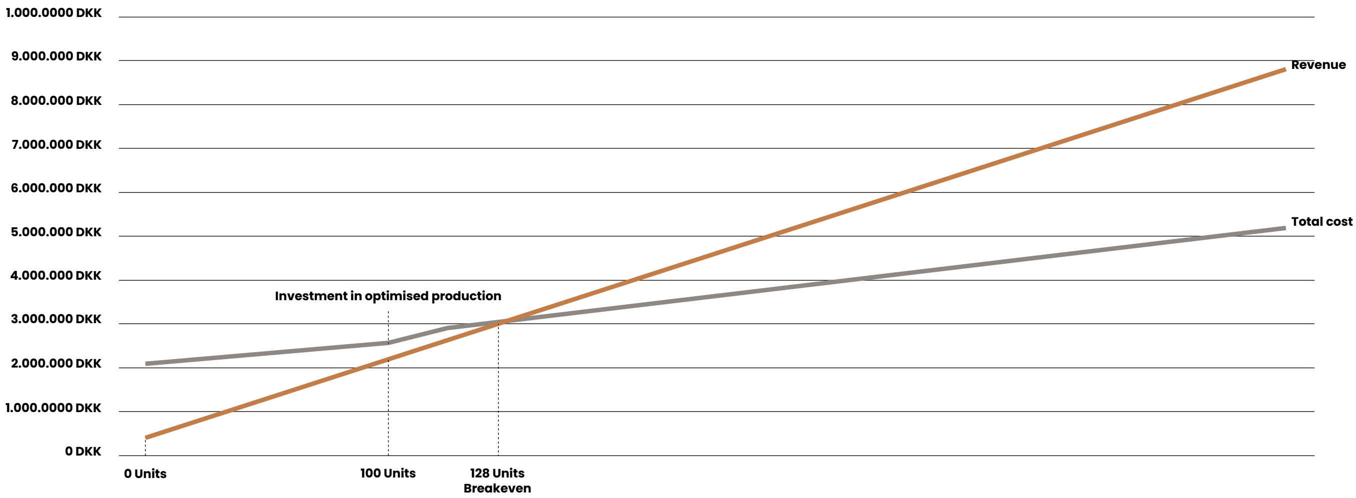
Introduction

The set sales price is based on the market's existing solutions with heavy consideration to the different products' cost-to-feature value. To position motus on the market in a way that not only fills a price gap but also fits the vision of an everyday product, the sales price is set to 22.000 DKK.

The breakeven point occurs when all debts have been paid off and the business starts becoming profitable. Accounting for the initial start-up investment, the breakeven point with the standalone production is after 117 sold units. This number however does not give an accurate representation of reality as the first batch of products will be used as a proof of concept to garner credibility on the market. After 100 sold units, or perhaps sooner, the company would invest in moulds and start a collaboration with a micromotor business to produce the product as intended.

Scandinavia							
Budget	Year 0-5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11
Part sold	-	20	30	50	50	60	80
Sales price (factory)	-	22.000 DKK	22.000 DKK	22.000 DKK	22.000 DKK	22.000 DKK	22.000 DKK
Product cost	-	5688 DKK	5688 DKK	5688 DKK	9190 DKK	9190 DKK	9190 DKK
Turnover	-	440.000 DKK	660.000 DKK	1.100.000 DKK	1.100.000 DKK	1.320.000 DKK	1.760.000 DKK
Variable cost	-	116.160 DKK	174.240 DKK	290.400 DKK	407.150 DKK	488.580 DKK	651.440 DKK
Contribution margin	-	323.840 DKK	485.760 DKK	809.600 DKK	692.850 DKK	831.420 DKK	1.108.560 DKK
Investment	- 2.000.000 DKK	- 2.000.000 DKK	- 1.676.160 DKK	- 1.190.400 DKK	- 408.452 DKK	+ 284.398 DKK	+ 1.115.818
Contribution	-	323.840 DKK	485.760 DKK	809.600 DKK	692.850 DKK	831.420 DKK	1.108.560 DKK
Remaining	- 2.000.000 DKK	- 1.676.160 DKK	- 1.190.400 DKK	- 380.800 DKK	+ 284.398 DKK	+ 1.115.818 DKK	+ 2.224.378 DKK

Therefore, the company would realistically first reach a breakeven 9 years after initial investment; 4 years after the official launch, having sold 100 units from the standalone production and about 28 units from the optimised production.



ill. 157. Cost volume profit graph

Reflection: Cost precision

All calculations are rough estimates to get a sense of the expenses, however there are still many unknown factors, such as the specific development costs, software optimization and the cost of the interface. It is furthermore assumed that the initial investment might be higher than first estimated.

Platform & scaling

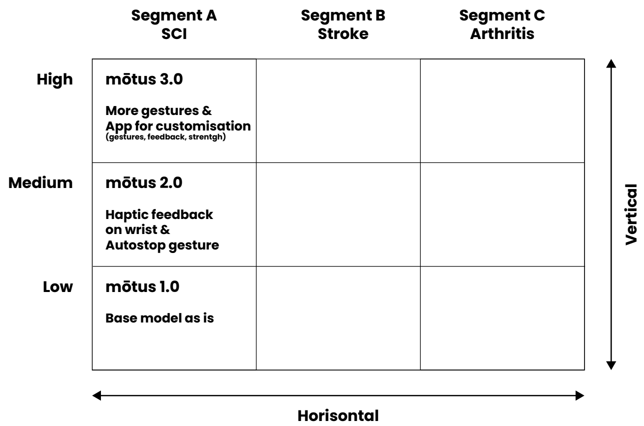
Introduction

The following chapter reflects upon the future potential of motus and scaling options which would ensure a stronger market positioning. It also illustrates the product platform and modular architecture, which enables motus to be customised and upgraded for different user segments and preferences.

As a continuation of the previous research, this product has high scaling potential onto other user segments with similar injuries and needs, which might enlarge the market potential remarkably. The team has reflected on including target groups with injuries and diseases such as; stroke, traumatic injuries (dislocation or nerve damage in the hand), ALS and rheumatoid arthritis, which are all cases with increased risk of immobility in the hands. As an example, including just stroke patients in the market scope, 75% (Belluck, 2023) of them experience hand paralysis, which is approximately 172.500 individuals in Denmark currently, with 15.000 new cases each year (Hjerneskadeforeningen, 2021). Including these segments a horizontal scaling greatly increases the market size and potential for the proposal.

mōtus 2.0 and mōtus 3.0

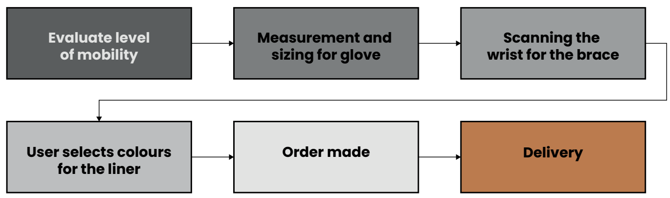
The user's mobility level and need for aid varies a lot within the user segment, and no injury is like the next. This might result in varying product requirements to functionality and usability. Therefore the product proposal has high potential for vertical scaling, where each level has additional features to cover these requirements. After having developed on motus 1.0, with low complexity and functionality, the team has reflected on the inclusion of an upscaled version 2.0 and 3.0 which would target a different user group. The prices of these would be accordingly, and therefore the motus brand would reach further out on the market to compete with the competitors.



ill. 158. Scaling

Fitting scenario

The fitting scenario was mapped out to predict what the fitting and purchasing process might entail for both user and company. The first consultation and fitting will determine the users mobility level and glove size, and from here the user can customise their product according to their preference, and the product will be delivered. The product will have yearly check-ups to ensure it functions as intended.

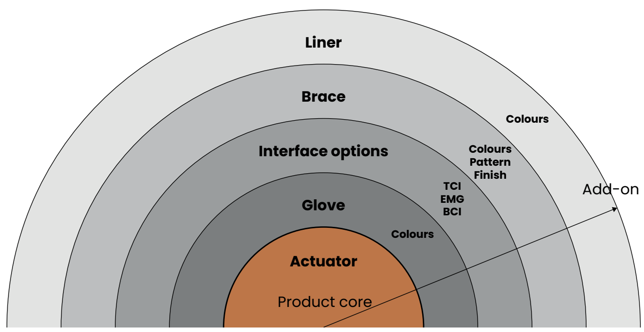


ill. 159. Fitting scenario

Design platform

The design platform and product architecture has been designed to enable customization for each specific user. This also enables both horizontal and vertical scaling, as parts of the solution can be interchanged or reprogrammed. The model (ill. 156 and 160) shows the product architecture which consists of both integrated and modular interfaces.

Motus is separated into parts and subparts, which altogether make up the final design. The customer, at first purchase, will be fitted for all layers of the product. Their mobility level will be assessed and the actuation module and needed interface will be programmed. From here motus is built outwards and the user can freely choose between a variety of colour and mix to their preference.



ill. 160. Design platform

Epilogue

Phase 8

The design proposal is evaluated by comparing it to the problem statement and initial goals. Throughout the process, the synergy between abstraction levels have been evaluated after each phase. Now, the proposal will be evaluated in its entirety, from the initial stages to the finalisation, and whether it fulfils the goals set for the project scope. Lastly, a reflection on the process and the product discussing the key take-aways from the project. To this, a discussion where the product reaches the goal of being implementable into everyday life and where it falls short, and more importantly why this was the final outcome?

Conclusion

This project aimed to create a next-generation exoskeleton glove for disabled. This redesign was intended to change the current view on exoskeleton products, transforming them into socially accepted objects that could seamlessly be integrated into everyday life and become a symbol of independence rather than disability. A direction that as of now has been an unsuccessful endeavour.

After interviewing tetraplegics, the REROB team and other experts on the field, the thesis team discovered that exoskeletons are currently a product category in which the user needs to adapt to the product and not vice versa. The lack of a strong user-product relationship, along with minor thought to a holistic view where function, application and aesthetics synergise, make exoskeletons severely difficult to implement into daily living despite their massive benefit.

By investigating everyday scenarios and existing routines, the thesis team was able to identify which critical points needed to be accounted for in all three holistic areas. These insights gave leeway to slice the problem into easier tackled aspects that were then explored, tested and specified. In this regard, while working with all three areas of the holistic view, application was prioritised the least which leaves optimisation and further exploration to be desired in this particular area. As a whole, it should be noted that all tests were simulations that could only replicate chosen working principles to the team's best ability. Without creating a functional prototype with the correct specifications and testing it on the user segment over a longer period, the proposal's actual ability to be integrated into everyday life remains unknown.

Ultimately, the result of the process is the mōtus exoskeleton glove. A clothing-like take on exoskeleton design that prioritises identity creation and fitting into everyday life while enabling the essential functions. mōtus does not innovate on the mechanical construction but rather focuses on transforming a foreign object into something recognisable and personal. By becoming a physical and emotional extension of its user, it benchmarks a paradigm shift in the way we see exoskeletons

Reflection

Process

After being introduced to the REROB team, the thesis team found major intrigue working with a possibility to work on a problem where a significant impact could be made. The team had not encountered such an 'obvious' problem before, thinking "of course they need to be able to move" but simultaneously could not figure out where the actual contribution was: In what other ways do the product improve the user's quality of life? Moving forward, this question made it difficult choosing which areas of the holistic view should be prioritised the most as all three seemed instrumental for the success of the proposal.

Rabbit hole syndrome

For this project, the thesis team had a different point of entry than they had previously experienced. This entailed a collaboration with an external partner, the REROB group, and a preset assignment: creating a new design for the EXOTIC exoskeleton. However, the team could not simply execute on such a 'tame' problem. Having this type of point of entry into the project made it difficult to let go of the initial framing and problem space. This inability to see the problem from other perspectives meant the solution space could not evolve. The early action paralysis caused the process to remain stagnant for a long period because the team was afraid that if they pivoted to another problem space, they would not have a problem at all. Ultimately, reframing the scope of the project allowed for quickly unfolding new parameters, eventually cutting to the core of the problem with current exoskeleton design. In retrospect, the original assignment and the final problem statement ended up tackling the same theme: incorporating identity creation and visual identity into an foreign object to increase its usability.

User involvement

During the process, there was way less user involvement than anticipated. Here, the users were difficult to recruit due to their physical condition. The users, the team managed to get in contact with, needed to plan out meetings a long period in advance due to having pressing activities to attend to each day. In addition, the team wanted to treat the users with as much respect as possible, and therefore did not test their mock-ups on them. It would seem disrespectful to test a cut up gardening glove on a disabled individual. Instead, the team members acted out the role of tetraplegic to provide a simulated picture of real life. Nevertheless, the exact physical disability level was difficult to accurately replicate, making it more difficult to evaluate working principles in an actual use case. From the get-go a more systematic agreement should have been made with the users explicitly stating the team could use them in tests.

Prototyping

Delving into 'uncharted territory', there was a large drive to uncover as many aspects as possible. There were no preconceptions which proved an advantage in creating a framing that made sense for the project scope as a whole. This also proved to be one of the bigger hindrances during the development. The team did not have the competences nor resources to properly test the proposal; sourcing the correct materials and programming the electronics. To combat this, problem slicing was used to break the problem's complexity down to tangible areas that could be tested through primitive mock-ups. Despite providing many insights into the product's usage, the lack of 'real' prototypes also introduced uncertainties when evaluating concepts and ideas.

Product

The mōtus exoskeleton glove still needs further testing on all three holistic areas. At this point, it is only on a detailed conceptual level. Experts and users should be reintroduced into the project to properly test the proposal with the intended working principles.

Function

The choice of enabling three hand gestures creates a big compromise in the size, strength and requirement of the motors and battery comparatively to if all fingers moved in synchronisation. This choice was deemed necessary for the user to move as naturally as possible. There is, however, an uncertainty whether the chosen functions provide adequate versatility to perform well in an everyday context or if they are unnecessary and a stronger grip could solve the problem. This compromise needs to be addressed through actual use cases with a prototype.

Application

One of the major aspects of using the product is to wear it. How the product is worn is one of the key areas where the existing solutions fall off, making it incredibly important for the holistic picture. Not only the glove but also the actuation module. As the team focused most of the process proving the functional aspect: enabling movement that mimics human anatomy, there was not as much focus on this part as wanted despite it being half of the physical product. In a different scenario, there would have been more resources allocated to the actuation module but this compromise was deemed necessary to make to even reach a proposal that could function.

Aesthetics

The aesthetics of mōtus is where it differentiates itself the most from classic exoskeleton design, seeking to push the industry into a new era with greater considerations to self-image and identity, yet enabling adequate essential functions to be usable in everyday life. The new design language creates a design push which likely requires an adoption period for the product. It is unknown whether the customization possibilities will be used, especially with the brace, or they will stick to one product setup combination at all times. Nevertheless, statements from users and experts point towards a massive grey spot in this area. To obtain a final validation, different users should be contacted after the hand-in to provide feedback on the design and platform possibilities of the proposal.

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Illustrations

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119-121: Own illustrations, generated in Midjourney
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mōtus

Content

Disclamer

Parts of the following technical drawings are constructed based on the dimension of one individual. The dimensions would therefore be relative to the specific case.

Aalborg University

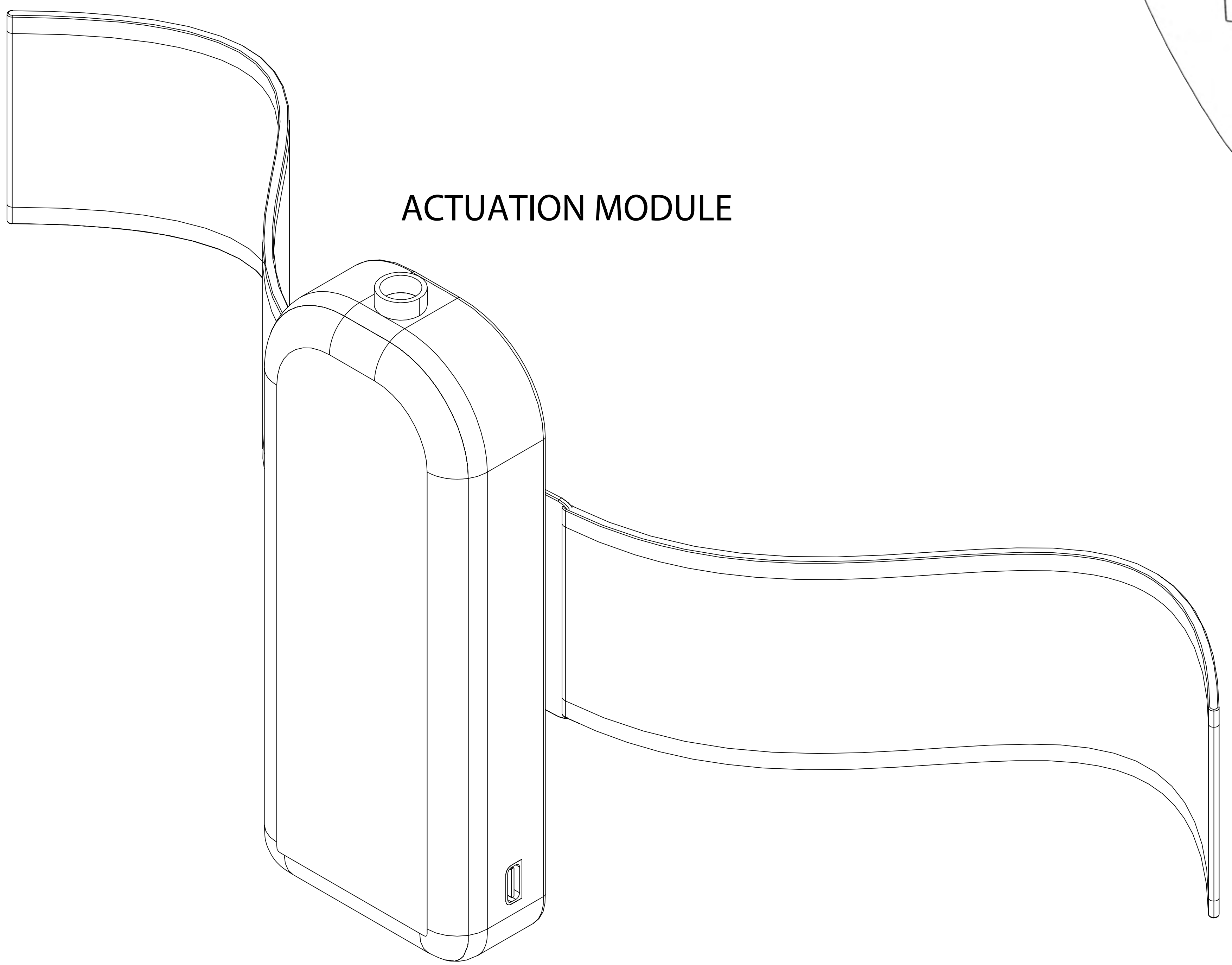
Industrial Design
Master's thesis

Technical drawings

Spring 2023
31st of May

MA4-ID3

Danny Chau Huynh
Sofie Busch



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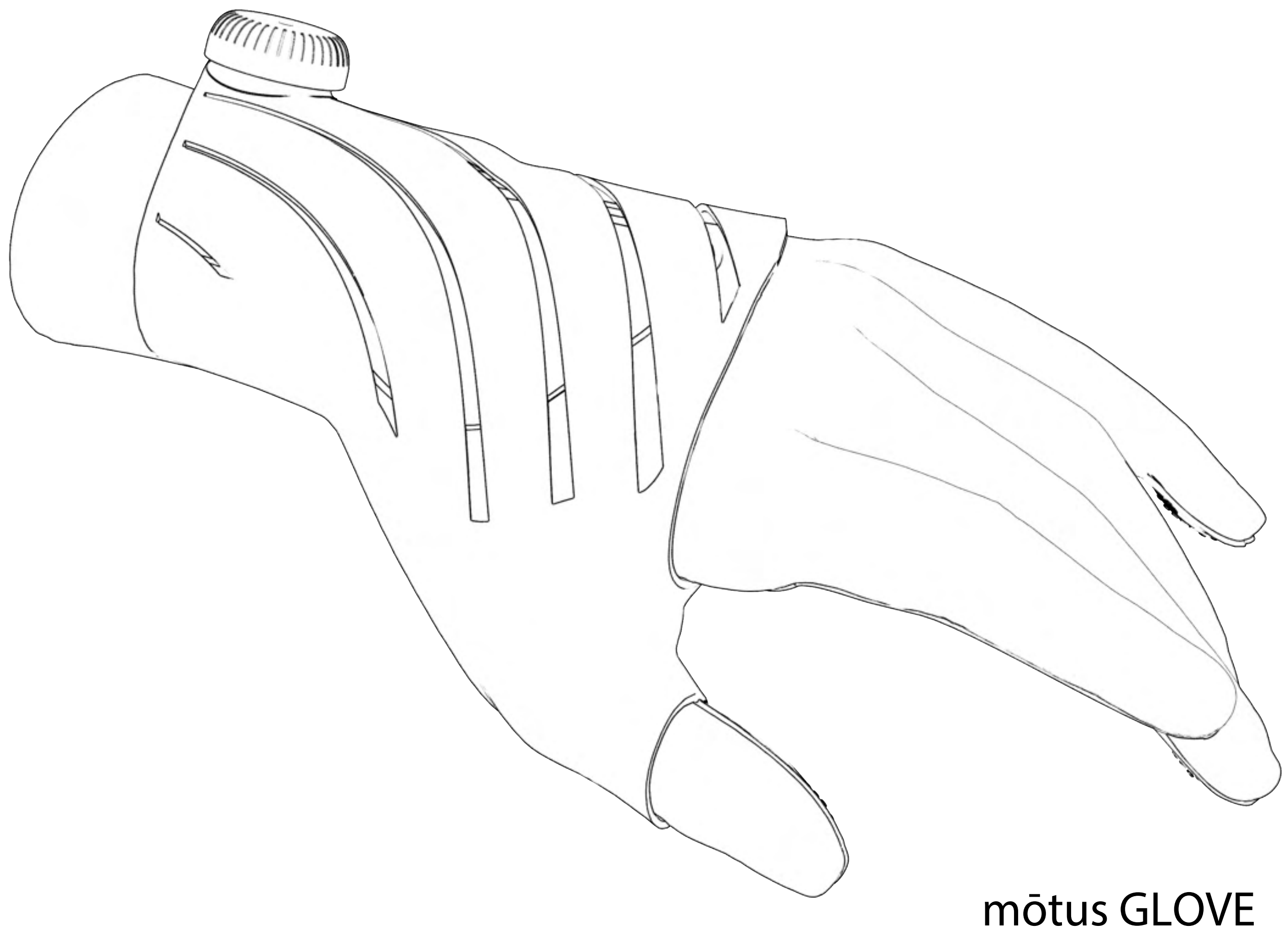
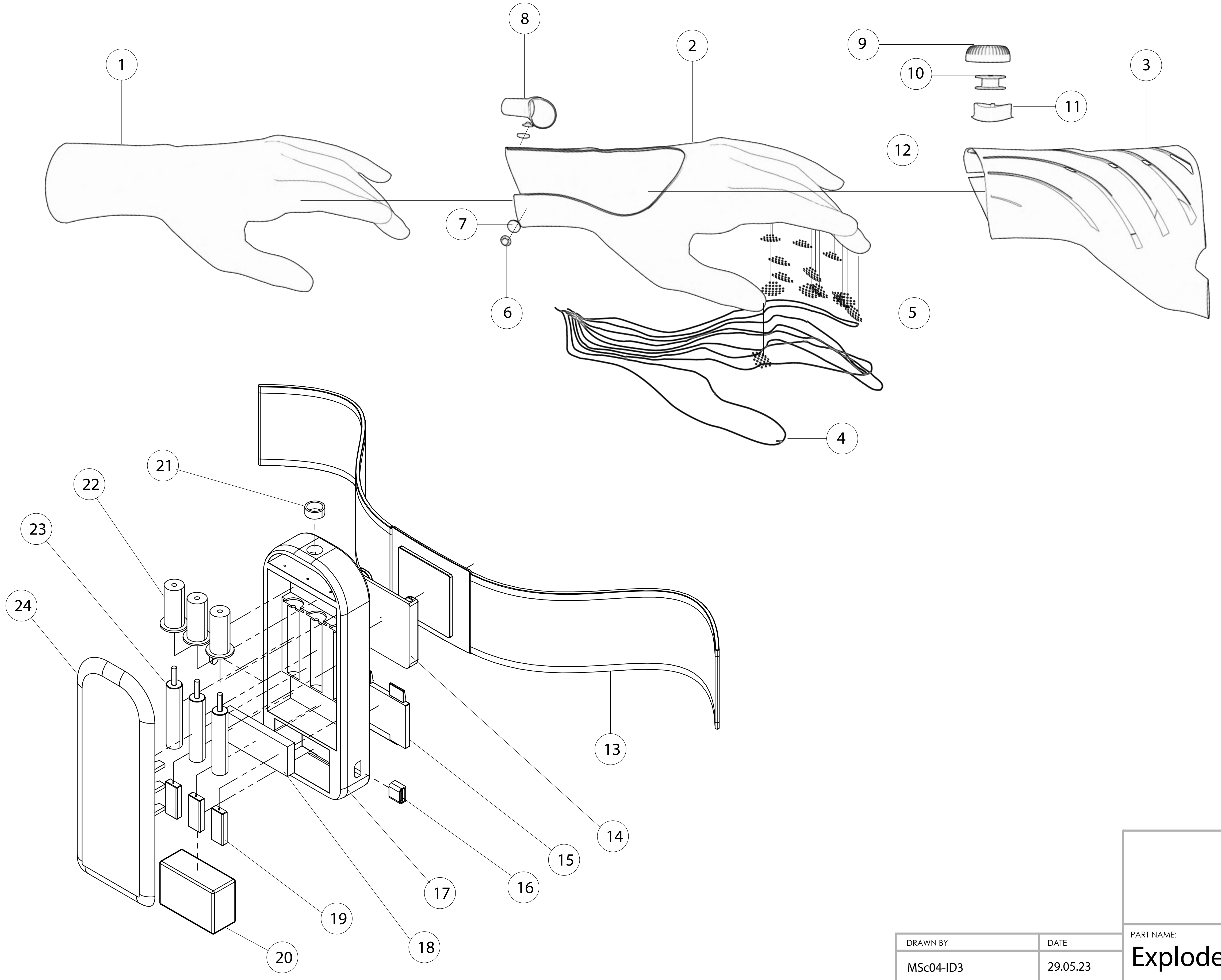


mōtus GLOVE

PROJECT:
mōtus
Industrial Design Msc04
Master's thesis

DRAWN BY	DATE	PART NAME:
MSc04-ID3	29.05.23	Main drawing
MATERIAL:		PART NO.: A3
TOLERANCES		SCALE:1:1 / SHEET 1 OF 7



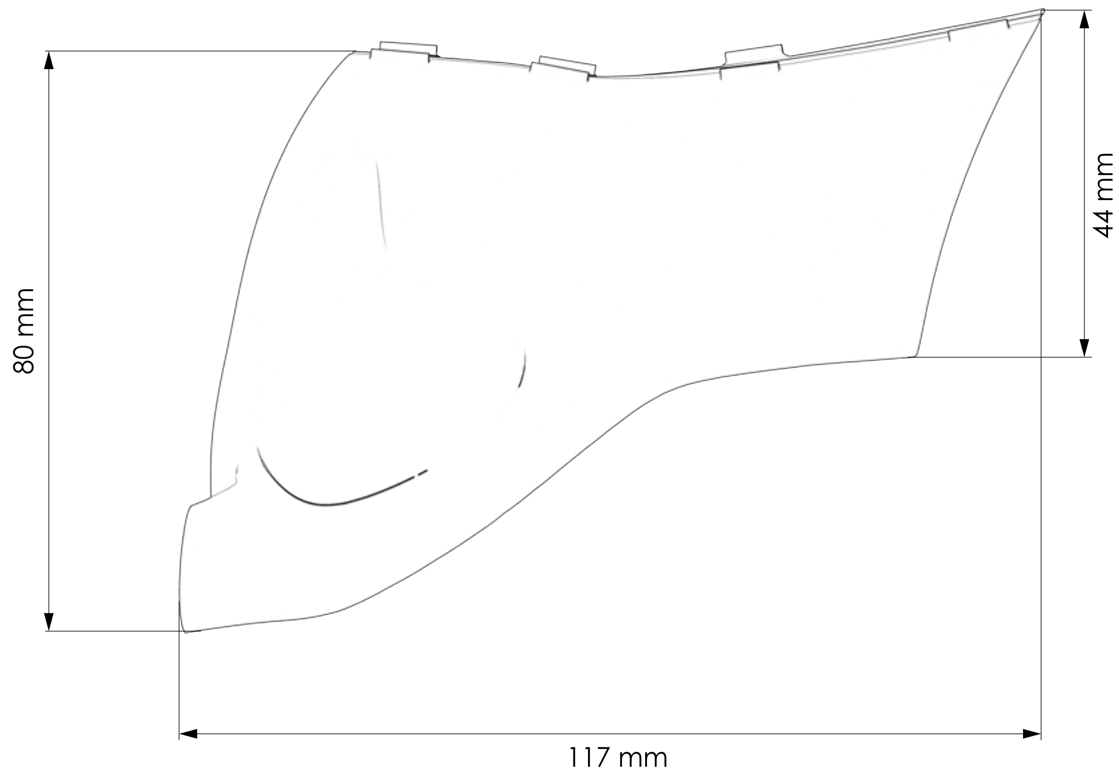
PROJECT:
mōtus
Industrial Design MSc04
Master's thesis

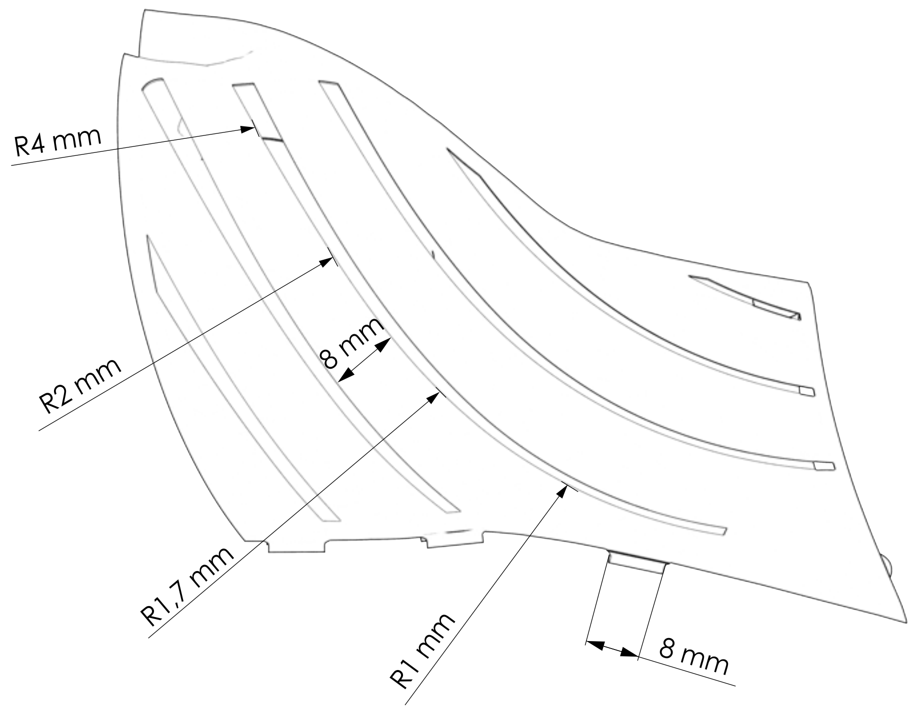
DRAWN BY	DATE	PART NAME:
MSc04-ID3	29.05.23	Exploded view, mōtus
MATERIAL:		PART NO.: A3
TOLERANCES		SCALE: 1:2 / SHEET 2 OF 7

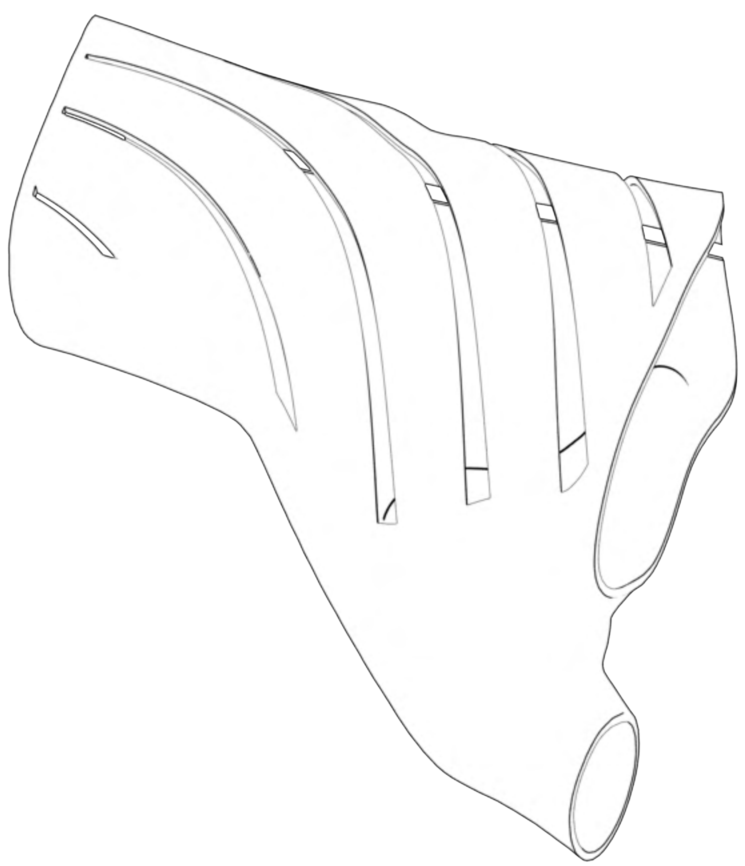
PART NO.	PART NAME	MATERIAL	QTY.	STD./CSTM.
1	Glove liner	75% Bamboo Rayon, 25% Elastane, Polyamide blend Elastics interwoven	1	CSTM.
2	Glove	COOLMAX polyester fibres	1	CSTM.
3	Brace	Lorem ipsum	1	CSTM.
4	Artificial tendons	Dyneema string and teflon tube	5	CSTM.
5	Rubber grippy	Silicone	N/A	CSTM.
6	Snap fastener (female)	POM	2	STD.
7	Snap fastener (top)	POM	2	STD.
8	Cord exit	ABS	1	CSTM.
9	Dial lock (top)	POM	1	STD.
10	Dial lock (drum)	POM	1	STD.
11	Dial lock (bottom)	POM	1	STD.
12	Snap fastener (male)	POM	2	STD.

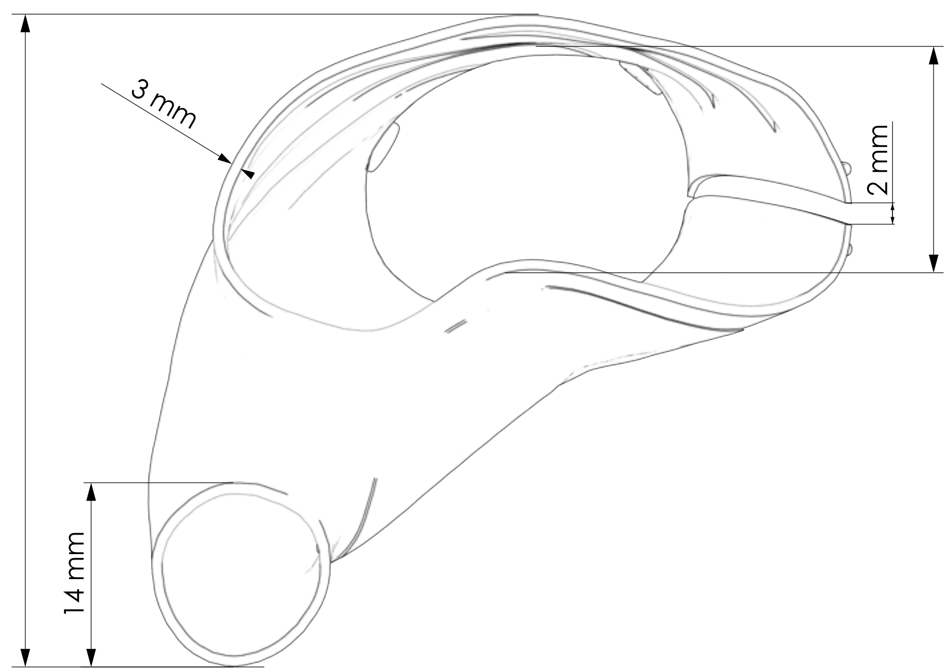
PART NO.	PART NAME	MATERIAL	QTY.	STD./CSTM.
13	Cold mount strap	Nylon	1	CSTM.
14	Cold mount	ABS	1	STD.
15	Battery lid	ABS	1	STD.
16	USB port	ABS	1	STD.
17	Motor house	ABS	1	CSTM.
18	Microcontroller	N/A	1	STD.
19	Motor controller	N/A	3	STD.
20	Battery	N/A	1	STD.
21	Cord exit	ABS	1	CSTM.
22	Drum	POM	3	CSTM.
23	Micro DC motor	N/A	3	CSTM.
24	House lid	ABS	1	CSTM.

PROJECT:	mōtus Industrial Design Msc04 Master's thesis
DRAWN BY	MSc04-ID3
DATE	29.05.23
PART NAME:	BOM, mōtus
MATERIAL:	
PART NO.:	
	A3
TOLERANCES	
SCALE:	
SHEET 3 OF 7	

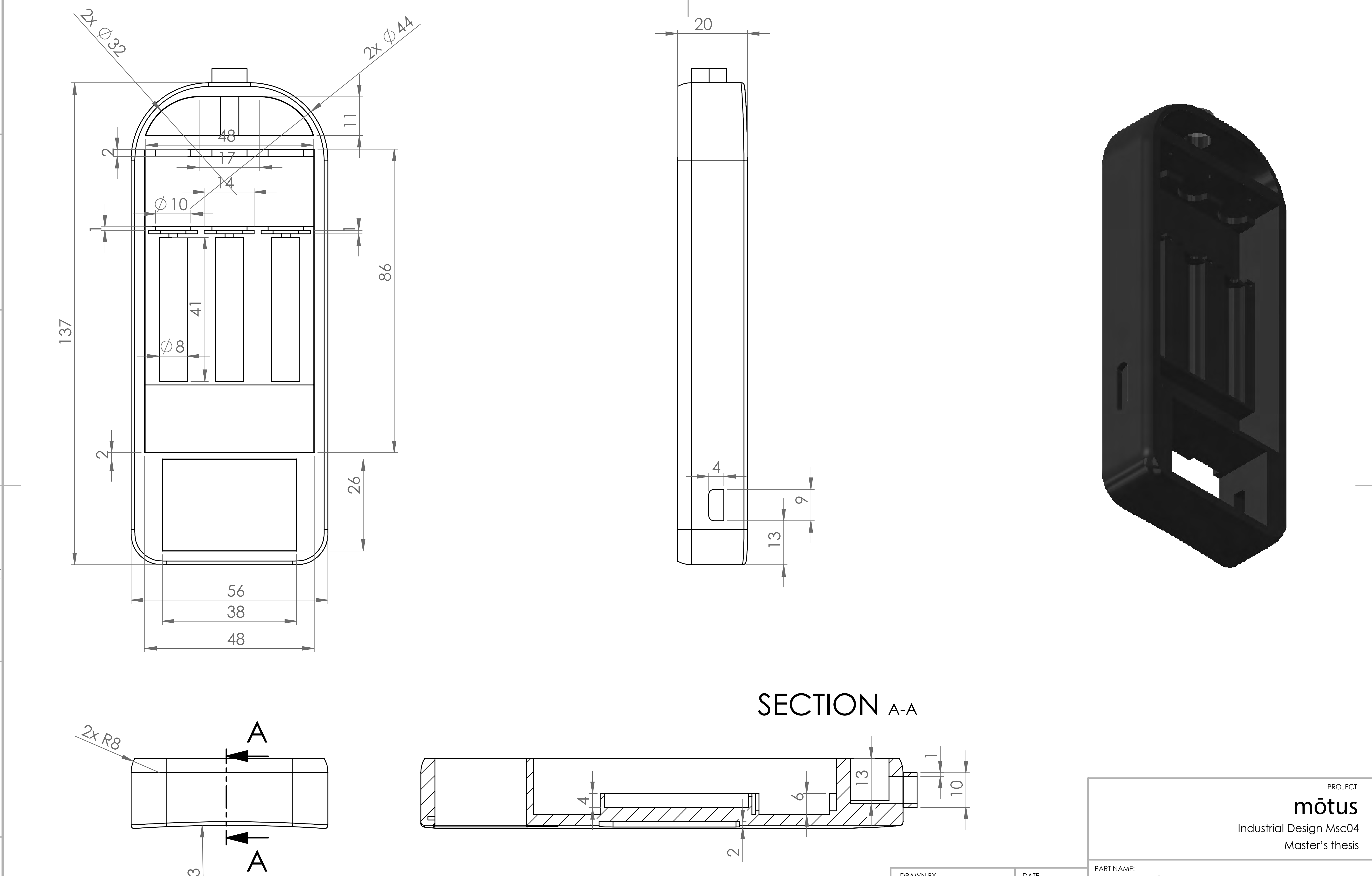








PROJECT:	mōtus Industrial Design Msc04 Master's thesis
DRAWN BY: MSc04-ID3	DATE: 29.05.23
PART NAME:	Detail: Brace design 1
MATERIAL: ABS, 3D scan, 3D printed	PART NO.: 3 — A3
TOLERANCES: DS/ISO 2768-1-m	SCALE:1:2 — SHEET 4 OF 7



PROJECT:
mōtus
Industrial Design Msc04
Master's thesis

DRAWN BY	DATE
MSc04-ID3	31.05.23

MATERIAL:
ABS, injection moulded

PART NAME:
Motor house

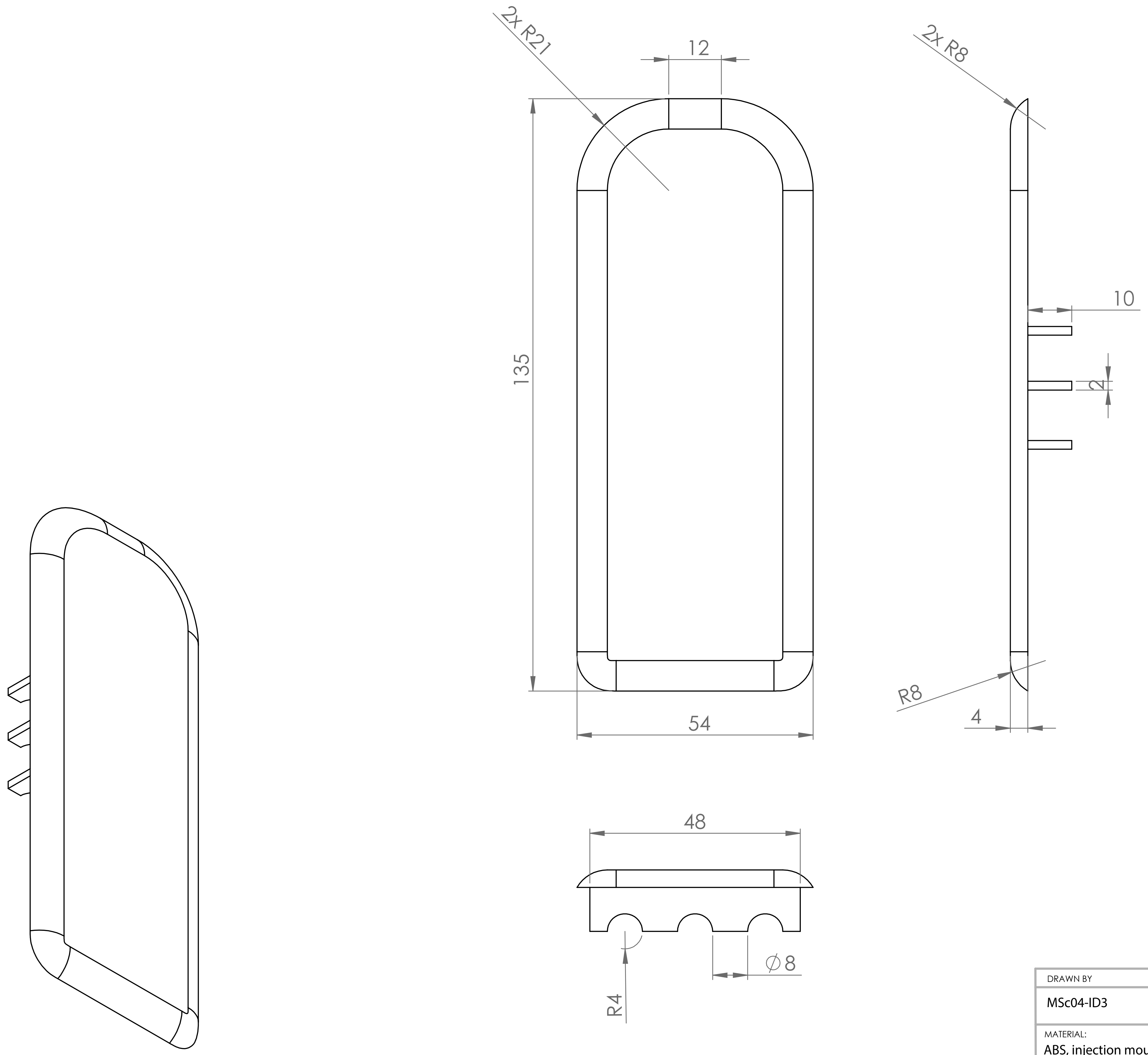
PART NO.:
17

A3

TOLERANCES: DS/ISO 2768-1-f

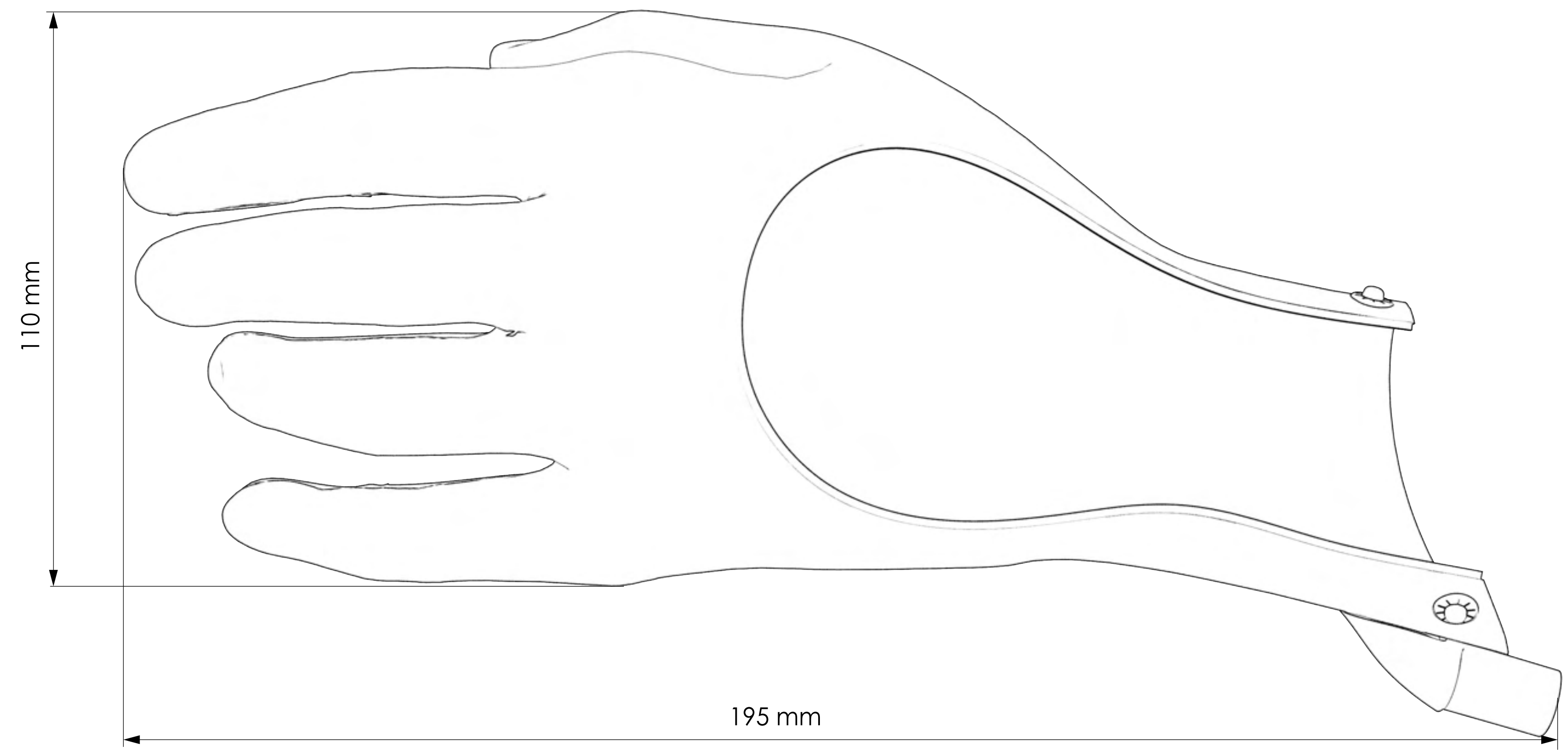
SCALE:1:1

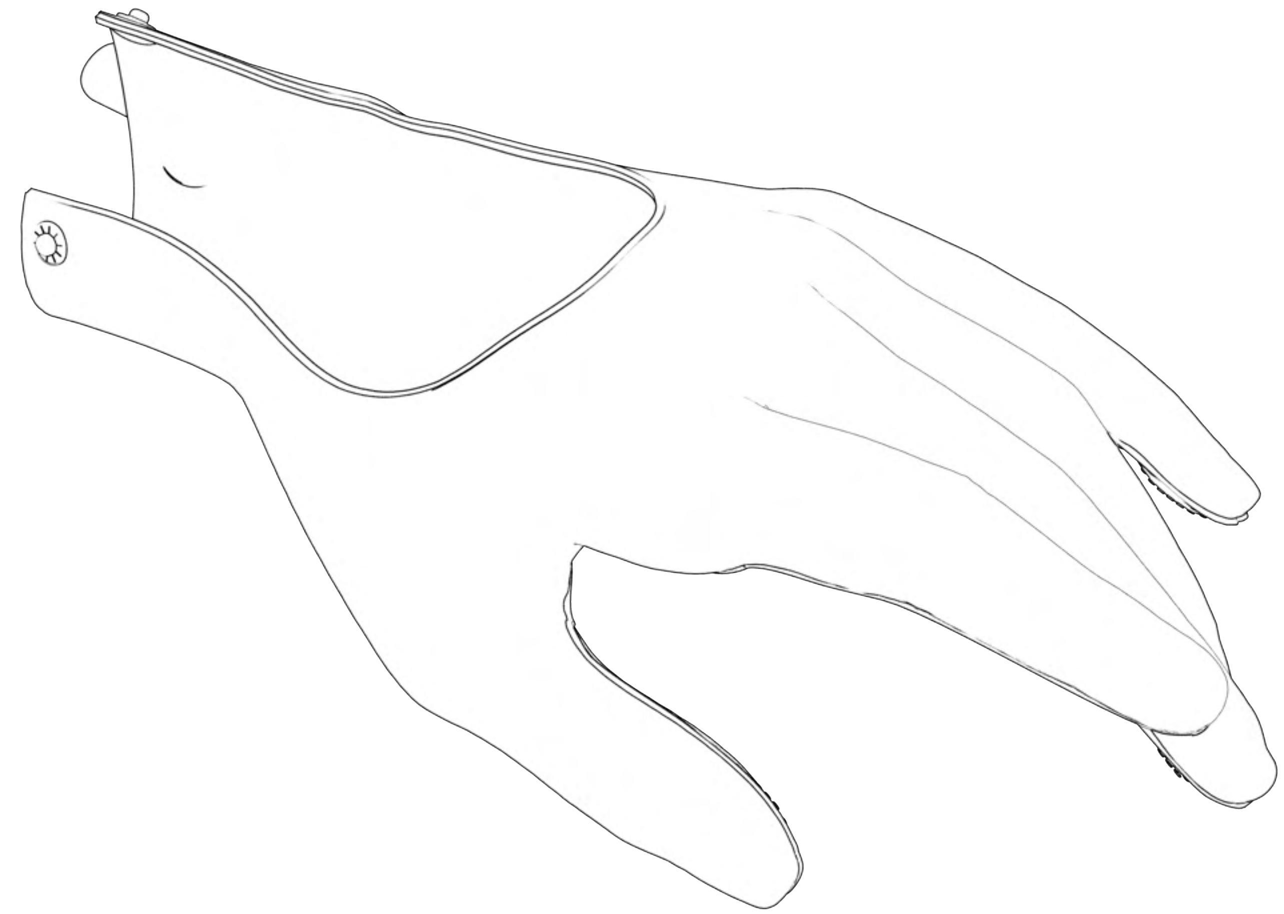
SHEET 5 OF 7

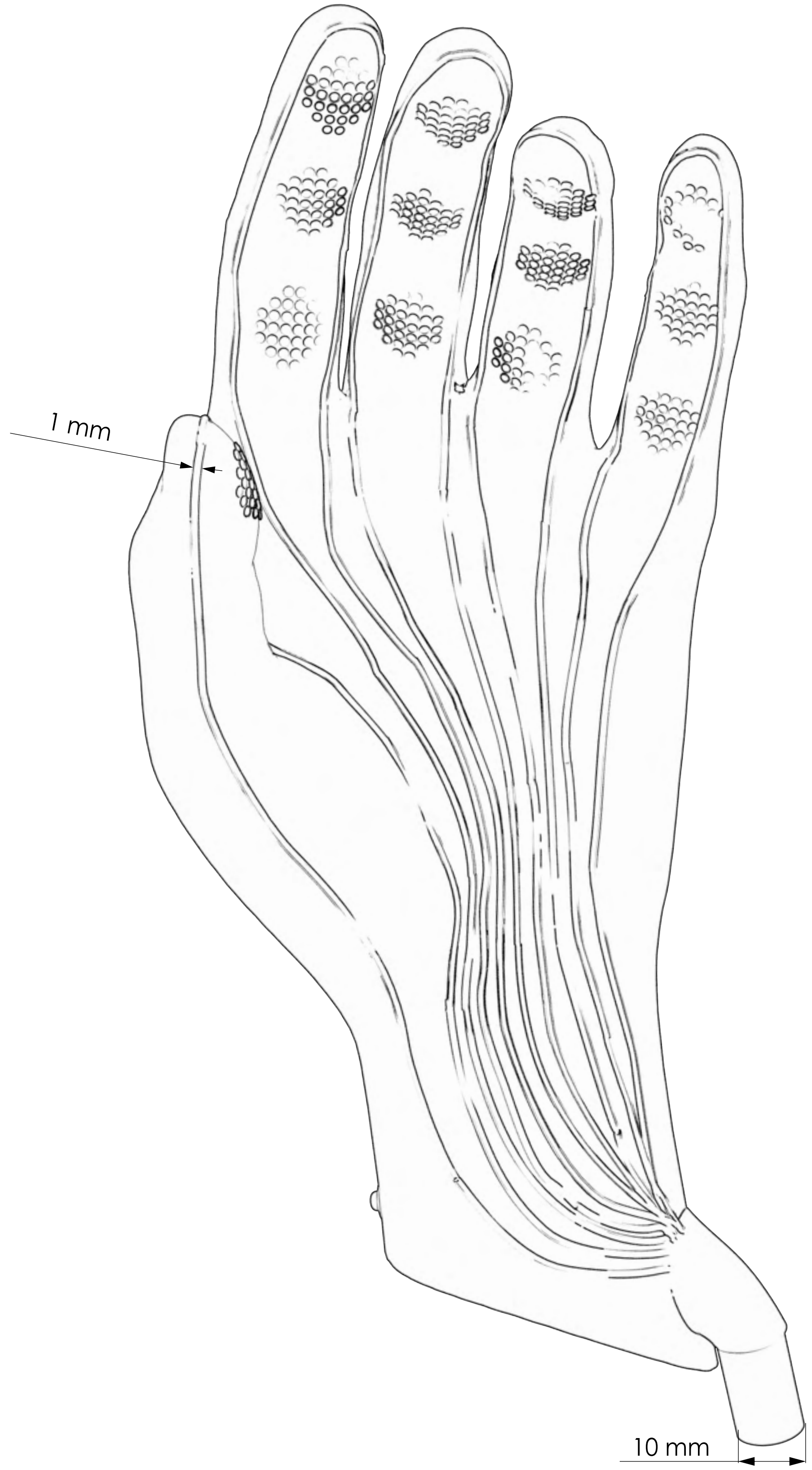


PROJECT:
mōtus
Industrial Design Msc04
Master's thesis

DRAWN BY	DATE	PART NAME:
MSc04-ID3	31.05.23	House lid
MATERIAL: ABS, injection moulded		PART NO.: 24 — A3
TOLERANCES: DS/ISO 2768-1-f		SCALE:1:1 — SHEET 6 OF 7







		PROJECT: **mōtus** Industrial Design Msc04 Master's thesis
DRAWN BY MSc04-ID3	DATE 31.05.23	PART NAME: **Glove**
MATERIAL: COOLMAX polyester fibre integral knitting		PART NO.: 2 A3
TOLERANCES: DS/ISO 2768-1-f		SCALE:1:1 SHEET 7 OF 7