Hand trainer for upper limb rehabilitation

Redesign of a minimally-supervised portable hand trainer for upper limb rehabilitation after stroke.

Master thesis | Eline Nathalie van der Stoep

TUDelft Delft University of Technology

Erasmus MC

RIJNDAM VERBAAS JEZELF

Colophon

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Author
Eline Nathalie van der Stoep

Supervisory team
Prof. dr. ir. Goossens, R.H.M. (chair)
Dr. ing. Marchal-Crespo, L. (mentor)
MSc. Ratschat, A.L. (daily supervisor)

In collaboration with
Motor Learning and Neurorehabilitation Lab, 3mE Faculty, TU Delft
Rijndam Revalidatie, Rotterdam
Department of Rehabilitation Medicine, Erasmus Medical Center

Preface

Dear reader,

I am happy and above all proud to share my graduation thesis with you. This booklet marks the end of a special era: being an Industrial Design Engineering student in Delft, the city that I also grew up in. The moment I am writing this, I feel extremely proud but also sad to leave seven memorable years behind.

In the past years, I have created a great passion for designing in the medical field, so starting my graduation project at the MLN Lab of the Cognitive Robotics department at 3mE did not come as a surprise for people who are close to me. Strokes are, unfortunately, a common disease nowadays, and I am grateful that I got the opportunity to contribute to the rehabilitation process that patients go through after an incident.
I want to thank the **MLN Lab** for being part of their team for the past five months. It was a pleasure to work alongside a close, interdisciplinary group of dedicated and talented people.
A special thanks to **Alex Ratschat** and **Laura Marchal-Crespo** for all the fun and insightful meetings, challenging me to develop new skills, discussing ideas from different angles, introducing me to experts in the field and shaping the project.
Thank you for sharing your passion, expertise and unique ideas and insights.

Also, a special thanks to **Richard Goossens**, who has supported and guided me from the IDE side throughout my graduation journey. Thank you for our insightful, inspiring and sunny meetings. Your expertise and knowledge in the field inspired, motivated and challenged me. I am grateful to have had the opportunity to work with you.

I would also like to thank **Rijndam** for the close collaboration throughout my graduation project. Thank you to all the therapists, doctors and engineers for their time, flexibility, thoughts and valuable feedback.

Lastly, I want to thank my family and friends. Thank you for your laughs, your distraction, your delicious food and drinks, studying in the sun and reserving 3D printers when I was not able to.

By presenting this work, I hope we can take a small step forward again to improve the rehabilitation process of stroke patients.

Enjoy reading,

Eline

Executive summary

People that are recovering from a stroke need frequent and high-intensity training to regain their upper-limb capacity. This will eventually result in better performances and higher quality of their daily life. Robotic devices are often used to assist stroke patients in rehabilitation. The minimally-supervised portable hand trainer, which is currently developed at the Motor Learning and Neurorehabilitation Lab of the TU Delft, specifically focuses on hand and forearm rehabilitation.
Haptic feedback is used in a virtual game to train patients' finger flexion and extension and forearm pronosupination.
Prior to this master thesis, a feasibility and usability study has been performed with the second iteration of the hand trainer in collaboration with therapists from Rijndam and healthy participants, showing room for improvement.

In this graduation project, the portable hand trainer is redesigned to develop an improved product design in comparison to the second iteration. Following a human-centered design approach, a modified version of the double diamond method (Chapter 1.5) followed to achieve a redesign that enables more functional, ergonomic, and motivating rehabilitation training.

Analysis on strokes (Chapter 2.1), on rehabilitation (Chapter 2.2), on the state-of-the-art (Chapters 2.4, 3.1 and 3.2), through peer tests (Chapter 3.3) and on the usability study (Chapter 3.4), were performed to create a decision matrix to define a list of improvements, distinguishing high-priority, medium-priority and low-priority improvements, discussed in Chapter 4.4.
The high-priority improvements have been thoroughly addressed in multiple cycles of ideation-, developing- and validating activities.
The results are combined and transformed into a hardware-ready 3D prototype that demonstrates improvement in the pronosupination movement, the donning and doffing of the device and the wrist support (Chapter 6). The prototype of the third iteration of the portable hand trainer is evaluated through interviews with experts in the field to reflect on the project goal and propose recommendations on future work, discussed in Chapters 7, 8 and 9.
The medium-priority improvements have been addressed in one cycle of ideation activities of which the results are presented in sketches to advice on further development.
The low-priority improvements have not been addressed in this project.

Terminology

ADL
Activities of Daily Living, such as cooking or doing the laundry.

Doffing
The act of doing a certain thing (in this thesis: the hand trainer) off.

Donning
The act of doing a certain thing (in this thesis: the hand trainer) on.

Dorsal
Toward or at the back of the body, e.g., the heart is dorsal to the backbone.

Finger extension
Anatomical movement; increasing the angle between the fingers and the palm of the hand

Finger flexion
Anatomical movement; decreasing the angle between the fingers and the palm of the hand.

Focus Group
Group of experts who are stakeholders of this design project. It consists of a physical therapist, an occupational therapist, a doctor and two engineers.

Lateral
Away from the midline of the body, e.g., the arms are lateral to the chest.

Medial
Toward or at the midline of the body, e.g., the heart is medial to the arm.

MLN Lab
Motor Learning and Neurorehabilitation Lab. An interdisciplinary research lab at the Human-Robot Interaction Group of the Cognitive Robotics Department of the Delft University of Technology.

Ventral
Toward or at the front of the hand, e.g., the breastbone is ventral to the spine.

Pronosupination
Anatomical movement; rotating the forearm about its longitudinal axis.

Spasticity
A common condition after a stroke incident that causes stiff or rigid muscles. It most commonly affects the elbow, wrist and ankle.

Usecue
Visual cues on a product that explain how a certain part is intended to be used.

Table of content

1 Introduction

Chapter 1 introduces the master thesis presented in this report. It gives an introduction to the project, the project owner (MLN Lab) and the approach to reach the project goal.

This chapter is structured in the following parts:

1.1 The project

Master Graduation Project | Integrated Product Design | Medisign

This graduation project is part of the master's program **Integrated Product Design** at the Faculty of Industrial Design Engineering at the Delft University of Technology.

The project is initiated by the **Motor Learning and Neurorehabilitation Lab** of the Cognitive Robotics department at the faculty of 3mE.

The portable hand trainer for minimally-supervised upper limb rehabilitation therapy is one of their ongoing projects. The first two design iterations have been developed at the University of Bern. And in 2022, a feasibility and usability study has been performed at the TU Delft in collaboration with therapists from Rijndam Rehabilitation Center and healthy participants, showing room for improvement on several aspects of the design. The goal of this graduation project is to deliver an improved product design in comparison to the second iteration.

This project is executed in a multidisciplinary research environment that offers close collaboration with mechanical and biomechanical engineers from 3mE, neuroscientists, and medical professionals from Erasmus MC and Rijndam Rehabilitation Center. A Focus Group, existing of a physical therapist (PT), an occupational therapist (OT), a clinician (C) and three engineers (E1, E2 and E3), has been set up to run brainstorming sessions and evaluations.

1.2 Motor Learning and Neurorehabilitation Lab

The Motor Learning and Neurorehabilitation Lab (MLN Lab) is an interdisciplinary research lab that is part of the Cognitive Robotics Department at the 3mE Faculty of the TU Delft. The lab's research focuses on using robotic assistance and immersive virtual reality (VR) to aid motor learning and neurorehabilitation of people after neurological injuries, specifically strokes (MLN Lab, 2023). Immersive virtual reality and augmented reality are used to enhance patients' motivation and reduce their cognitive load during training. One of their ongoing projects is the development of the **portable hand trainer**, which focuses on hand and forearm rehabilitation after a stroke incident. This graduation project contributes to the further development of the portable hand trainer.

1.3 Problem definition

Upper limb rehabilitation for stroke patients

1.3.1 Problem definition

People that are recovering from a **stroke** need frequent and high-intensity training to **regain their upper-limb capacity** (Tollár et al., 2021) (French et al., 2016). This will eventually result in better performances and higher quality of their daily life, including the ability to perform common activities of daily living. Robotic devices are often used to help people with their rehabilitation. The minimally-supervised portable hand trainer is envisioned to contribute to this. Currently, much time and effort are required to set up robotic devices to be used at home, which leads to frustration and abandonment. Also, robotic devices tend to be bulky, expensive, and complex in use (Fritz et al., 2019). Thus, this project is addressing the challenge of further developing a user-friendly hand trainer that can easily be taken home and used with minimal supervision.

1.3.2 The hand trainer

In this paragraph, the second iteration of the hand trainer is introduced (Van Damme et al., 2022). The minimally-supervised, portable hand trainer is designed to **facilitate two movements**. According to Rätz et al. (2022), the training of finger extension, finger flexion and forearm supination has higher importance in upper-limb stroke rehabilitation than e.g., the independent movement of the index finger, the key grasp or elbow flexion.

> Flexion and extension of the hand
> Pronation and supination of the forearm

The thin shell allows to perform flexion and extension of the hand (Figure 2).
By tilting the device from left to right, pronosupination of the forearm can be performed (Figure 3). The device uses an electric motor to give **haptic feedback** and provide resistance or assistance during flexion and extension.

To correctly use the device, the wrist must be placed in the wrist support and the hand must be placed around the shell, as shown in Figure 2.
The device is connected to a **game** displayed on an external screen (Figure 1). By performing flexion and extension, cocktail glasses are filled with varying liquids. By performing pronosupination, the user can navigate between the cocktail glasses.

Figure 1. The game

Figure 2. Minimally-supervised portable hand trainer

1.4 Project assignment

An improved embodiment design of the portable hand trainer

1.4.1 The starting point

The starting point of this graduation project is the product design after the second iteration cycle, shown in Figure 3.

1.4.2 Project scope

Improvements will be made **to the embodiment of the product (hardware)** and evaluated throughout the course of this project, e.g., on ergonomics, usability, functionality and appearance. In addition, advice will be given on the graphical user interface and the design of the virtual game.

Excluded from the scope of this project are the software and electronic design of the product. A formal usability study with stroke patients using the final prototype is also excluded from the scope.

1.4.3 Project goal

The goal of this graduation project is to **deliver a hardware-ready, improved product design** of the portable hand trainer for minimally-supervised therapy.
More specifically, the redesign will be based on insights from the iterative design process, including context analysis, state-of-the-art analysis, ideation, prototyping, testing and evaluation. These activities will be elaborately discussed in the following chapters of this report. To validate whether the proposed redesign is an improvement, it will be tested and evaluated throughout and at the end of the project.

Design goal
I want to improve the current design of the portable hand trainer for minimally-supervised therapy of people after a stroke to enable more functional, ergonomic, and motivating rehabilitation training.

Figure 3. Minimally-supervised portable hand trainer

1.5 Project approach

Modified Double Diamond Method

This graduation project follows a **human-centered design (HCD) approach**. Since stroke patients cannot be involved in the design process, the project cannot be marked as a user-centered design approach. According to Melles et al. (2020), human-centered design is about discovering and understanding human needs and designing products or services that meet these needs, using methods such as shadowing, co-creation and usability testing.
The process to achieve HCD is explained using a modified version of the **Double Diamond Method**, visualised in Figure 4. The double diamond model is a widely used visualisation of using HCD in product development in the healthcare sector.

The design process is illustrated as two diamonds, combining diverging and converging phases. The first diamond represents the **exploring** phase and the **defining** phase. The second diamond represents the **developing** and **validating** phases. The multiple ideation cycles are visualised in the second diamond as infinite loops that cover the developing and validating phase. The corners of the two diamonds are rounded to emphasize that the design process is a nonlinear, iterative process instead of a consecutive process where two diamonds would follow up on each other in which events occur in a specific order. In essence, the four stages will be covered multiple times until the final goal is reached.

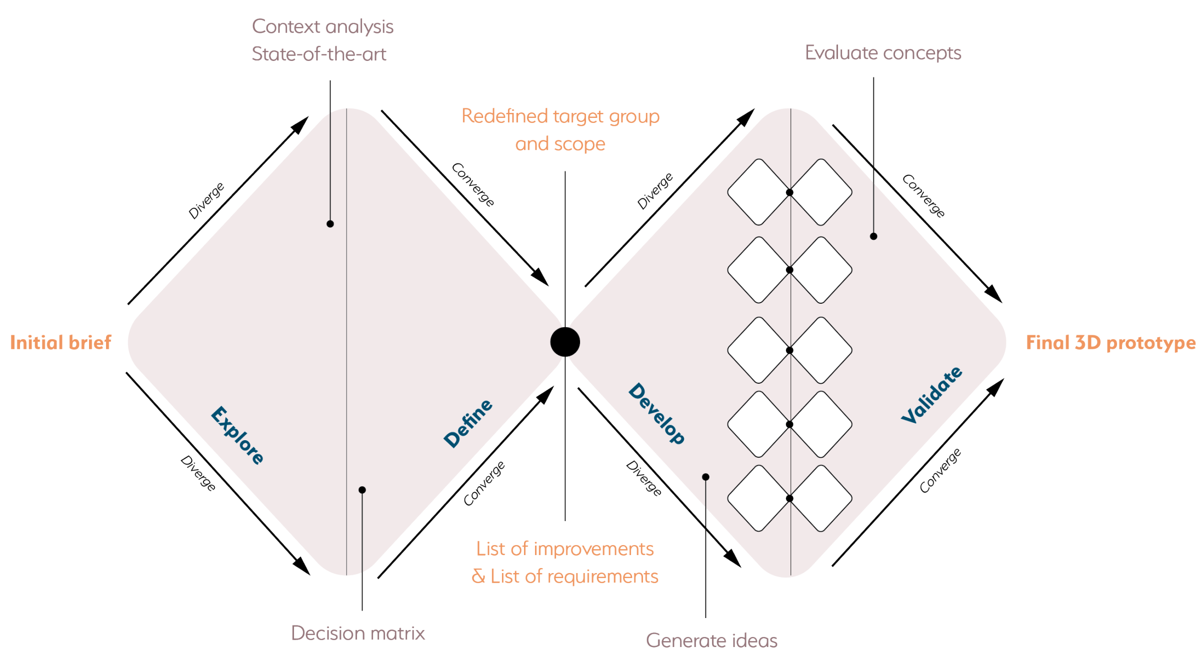


Figure 4. Project approach

2 Context analysis

This chapter introduces the context of the project by giving a brief introduction to stroke incidents, the rehabilitation process and program after stroke, the anatomical background of the human hand and forearm and presents an overview of currently existing rehabilitation devices on the market.

This chapter is structured in the following parts:

Explore

2.1 Stroke

2.1.1 Introduction
This chapter explores the causes and effects of stroke incidents and presents the characteristics of different types of stroke and how they can affect Activities of Daily Living (ADL).

2.1.2 Research questions

Main question:
What are the main causes and effects of different types of strokes?

Sub questions:
- How does a stroke occur?
- What types of strokes exist?
- Which people does it affect?
- What are the effects of (different types of) stroke?

2.1.3 Methods
Literature research: snowballing method
Interviews: semi-structured interviewing with a physical therapist and an occupational therapist (PT, personal communication, 2023) (OT, personal communication, 2023).
Observations at Rijndam Rehabilitation Center: shadowing, observing

2.1.4 Stroke incidents
Strokes, also called cerebrovascular accidents (CVAs), are the most common nervous system disorder worldwide. It can be considered the number five cause of death and the leading cause of disability in the United States. (Langhorne et al., 2011) (American Stroke Association, n.d.)
CVAs occur when a blood vessel, carrying oxygen and nutrients to the brain, is blocked. The vessel can be blocked in two different ways, distinguishing the two major types of strokes.

The first type, an **ischemic stroke**, is caused by a clot that is obstructing the blood flow through the vessel. Approximately 85% of all strokes are ischemic strokes. Around 15% of the strokes are **hemorrhagic strokes**, which occur when a blood vessel is ruptured and disrupts blood flow. A small percentage of the CVAs are categorised as either brain stem stroke or cryptogenic stroke. The latter is used in cases where the cause is undefinable. Brain stem strokes originate in blood vessels that deliver oxygen and nutrients to the brain stem. This type can paralyse both sides of the body, a so-called locked-in state. (Marieb & Hoehn, 2016) (American Stroke Association, n.d.)
Not all stroke incidents that occur are "completed". When all symptoms disappear within twenty-four hours, the unfinished strokes are called TIAs, transient ischemic attacks. The effects of a TIA are not permanent, but the occurrence of a TIA can be considered a warning for a serious CVA. (Marieb & Hoehn, 2016) (American Stroke Association, n.d.)

2.1.5 The effects
The physical and cognitive effects strokes have is depending primarily on the location of the blockage or rupture, the amount of brain tissue affected, and the type of stroke.

Blockage in the artery leading to the right cerebral hemisphere of the brain can cause paralysis on the left side of the body, vision problems, quick and inquisitive behavior, and memory loss. Blockage in the artery leading to the left cerebral hemisphere of the brain can cause paralysis on the right side of the body, speech/language problems, slow and cautious behavior, and memory loss.
A brain stem stroke can affect both sides of the body, resulting in a locked-in state. This disables movement below the neck and the ability to speak.

Thus, a stroke incident can affect many different functions of the human body and mind, i.e., paralysis, gross and fine motor skills, speech and language, cognition, vision, and emotion. In most cases, one side of the body is paralysed, and thus no or limited movement of the limbs is possible and may be accompanied by problems with balance and coordination. Often patients experience fatigue right after the stroke, which most commonly remains for a longer period of time. Spasticity is another common effect when people start trying to move limbs. Their muscles contract and become stiff and tight which can result in an abnormal position when not treated well. Sometimes, seizures occur. Seizures are painless brain malfunctions that can trigger body movements and behavior changes. The above-mentioned effects influence the ADL of people after stroke.
People can also experience cognitive, emotional and personality changes, of which depression and anxiety are two common effects. (American Stroke Association, n.d.)

Stroke can affect any person, however, some factors can higher the risk of experiencing a stroke in a lifetime. The top 10 leading risk factors in the world according to Feigin et al. (2022) include: high body mass index, high fasting glucose, air pollution, smoking, high LDL cholesterol, alcohol use, and low physical activity. Moreover, Feigin et.al. (2022) also mention that 63% of all strokes worldwide happen to people under seventy, thus it can no longer be seen as a disease of the elderly.

There are **12.2 million new strokes** each year, one every 3 seconds;
101 million people worldwide are living with stroke aftermath;
Globally, **1 out of 4 people** over age 25 will have a stroke in their lifetime.
Each year, **47%** of all strokes occur in men. **53%** occur in women;

Key insights

The great majority (85%) of strokes that occur **are ischemic strokes** and affect both men and women.

The effects of stroke are **dependent on the location** where the rupture or clot occurs, and thus which brain part is affected.

Depending on the parts of the brain that are damaged, the left, ride, or both sides of the body are affected. The **ratio of left/right-side paralysis is rather equal**.

Physical disabilities are **accompanied by cognitive and mental changes**. This needs to be considered while designing for upper limb rehabilitation.

The mental and physical status of a patient after a stroke can vary very much, so **one specific 'starting point'** of rehabilitation **does not exist**.

Spasticity is a common effect when stroke survivors start performing movements.

2.2 Rehabilitation

2.2.1 Introduction

This chapter addresses the characteristics of a rehabilitation process after a stroke incident and presents important movements to practice in upper-limb rehabilitation.

2.2.2 Research questions

Main question:
What do the different stages of a rehabilitation process after stroke include?

Sub questions:
- What does the rehabilitation process look like?
- What does the rehabilitation program look like?
- To what extent do different types of strokes have a different rehabilitation process?
- What exercises/training is involved in rehabilitation?
- What focus does each stage in rehabilitation have?

2.2.3 Methods

Literature research: snowballing method
Interviews: semi-structured interviewing with a physical therapist and an occupational therapist (PT, personal communication, 2023) (OT, personal communication, 2023).
Observations at Rijndam Rehabilitation Center: shadowing, observing.

2.2.4 Rehabilitation after a stroke incident

The first three months after a stroke incident are crucial. The brain characteristics are similar to a new brain at this point, it can adjust and re-wire itself, a process called **neuroplasticity**. Important connections between nerves in the brain are damaged after a stroke and during the process of neuroplasticity, nerves branch out and make new connections. After three months, neuroplasticity drastically decreases, and regaining functions takes place at a slower pace. Figure 5 shows the average recovery pattern of a person after a stroke incident with several intervention strategies for different stages in the process.
Important to note is that stroke recovery is heterogeneous in nature and is thus different for each stroke survivor. As mentioned before, the effects are dependent on the location of rupture, the extent of damaged brain tissue, and the type of stroke, however, the specifications of the consequences greatly vary for each survivor.

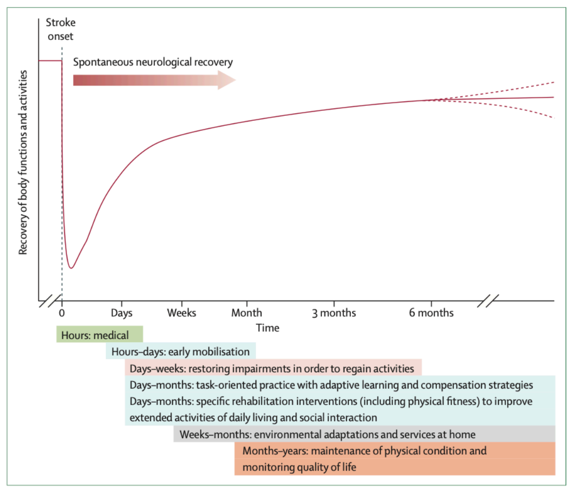


Figure 5. Pattern of recovery after stroke with intervention strategies (adapted from Langhorne et al., 2011)

2.2.5 Diagnosis

Since the symptoms of an ischemic stroke and a hemorrhagic stroke are not easy to differentiate at first sight, people who are showing symptoms will be examined by clinicians as soon as possible. The diagnosis includes i.e., identifying the medical history of the patient, physical and neurological examination, blood tests, and a CT/MRI scan. This information will help to identify the location of the injured brain area. Accordingly, early treatment can be performed for the identified type of stroke. For ischemic strokes, the clot can either be dissolved with a medicine called alteplase (tPA) or removed with a procedure called mechanical thrombectomy. Hemorrhagic strokes are treated either by using a catheter that leaves a coil at the location of the ruptured vessel or by securing the ruptured vessel at the base by surgery. The rehabilitation process is visualised in Figure 6.

2.2.6 Rehabilitation process

The period following a stroke incident can be organised into several phases, which are described in this paragraph and can be seen in Figure 7.
The first twenty-four hours after a stroke incident is defined as the hyperacute phase. The first 7-day week is the acute phase. Together with the early subacute phase, these three phases cover the period in which therapy is most crucial and effective because of the human brain's neuroplasticity, as mentioned before. The early subacute phase is followed by the late subacute phase, which covers the period from three months up to six months after the stroke incident. From six months onwards, patients go into the chronic phase. Recovery is at a slow pace, but improvements are still possible. In this phase, recovery is primarily seen through automisation of compensation strategies.

2.2.7 Rehabilitation program

After diagnosis and acute care are performed in the hospital, a rehabilitation program will be set up together with a specialised rehabilitation doctor. This generally starts with an intensive 24/7 program at an **Inpatient Rehabilitation Facility**, e.g., Rijndam Rehabilitation Center in Rotterdam. At Rijndam, the average time spent is fifty days. During these days, patients attend approximately 3 hours of therapy sessions each day, five days per week. This includes i.e., physiotherapy,

Figure 6. Process from stroke symptoms to start of rehabilitation program

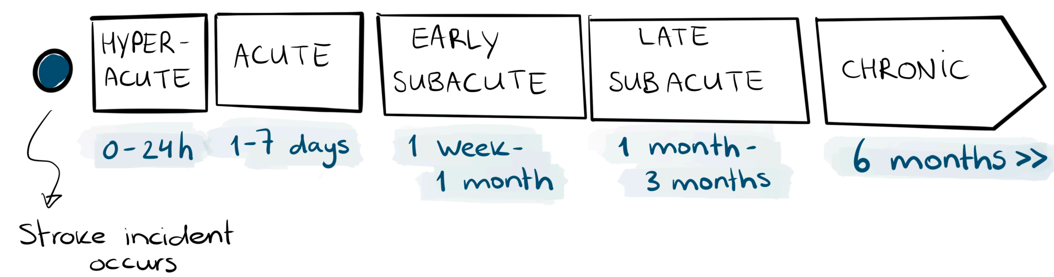


Figure 7. Rehabilitation process of stroke patients

occupational therapy (relating to Activities of Daily Life), recreational therapy, speech- and language therapy, psychological therapy and therapy in social work. Depending on the patient's capabilities and limitations, they will start at a specific level of difficulty and move up when progress is made, which is evaluated by short tests and self-reflection. (PT, personal communication, 2023)

At Rijndam, hand and arm therapy is divided into three groups, HAG 1, HAG 2, and HAG 3. HAG 1 is attended by patients whose hand and arm capabilities are zero to low. At HAG 2 and HAG 3, patients are motivated to train on their personal goals, often related to ADL such as doing the laundry, eating a meal, or buttoning up a blouse. At HAG 2, patients train to assist their unaffected hand in performing ADL. At HAG 3, patients train to use their affected hand to perform ADL. Patients spend three to four weeks on average in each group. However, some patients improve faster than others and thus move up quicker while a small amount improves too little and will instead focus on learning a new lifestyle using their unaffected side. Examples of exercises performed in HAG 1 are: sliding a towel over a table with the affected and unaffected hand, and turn the wrist left and right with the hands in a praying grip. Exercises performed in HAG 2 are: assisting the unaffected hand to cut bread, cutting clay (resembling a piece of meat), hanging up the laundry, picking up little objects from a rice bowl, turning cones (varying in weight) 180 degrees vertically and moving balls from basket to basket. Exercises performed in HAG 3 are: e.g., using a fork and knife to cut bread or meat, buttoning up and unbuttoning a blouse or hanging up laundry (Rijndam, n.d.) (PT, personal communication, 2023) (OT, personal communication, 2023). Some of these exercises can be seen in Figure 8, Figure 9, Figure 10 and Figure 11.

Inpatient care is in most cases followed by **outpatient care**. Patients who are no longer required to receive inpatient care and are not homebound will receive outpatient care. Patients go to the clinic for therapy sessions multiple times per week for a longer period. At Rijndam Rehabilitation Center, this is sometimes still accompanied by attending the HAGs.

Figure 8. Exercise materials from HAG 2 at Rijndam

Figure 9. Exercise materials from HAG 2 at Rijndam

Figure 10. Exercise product from HAG 2 at Rijndam

Figure 11. Exercise from HAG 3 at Rijndam: cutting meat

2.2.8 Upper limb rehabilitation

In research conducted with thirty-three participants (including physical therapists, occupational therapists, speech therapists, nurses and physicians), clinical needs for the then 'to-be-designed' hand trainer were analysed, explicitly focusing on upper-limb sensorimotor rehabilitation (Rätz et al., 2022). The participants were asked to judge the importance of practising various lower arm and hand movements. **Extension movements** in general appeared to be important during upper-limb rehabilitation. **In a talk with a physical therapist from Rijndam**, it was emphasised that extension movements are important because spasticity (e.g., cramped fingers) is a common effect amongst stroke patients (PT, personal communication, 2023). **Finger extension** and **supination** were considered the most important to practice, followed by the **cylindrical grasp**, **independent movement of the thumb** and **finger flexion**. Overall, finger extension is considered more important than finger flexion and forearm supination is considered more important than forearm pronation.

Finger flexion and extension

Flexion and extension of the fingers occur in the sagittal plane. Generally, flexion refers to a movement that decreases the angle between two parts of the body, and extension refers to a movement that increases the angle between two parts of the body. (Kapandji, 1982)

So, **flexion** of the fingers is performed by moving the fingers towards the palm. It has a range of approximately 90 degrees. Figure 12 illustrates how flexion is performed.

Extension of the fingers is performed when the angle between the fingers and the palm increases. The range of active extension can reach 30 or 40 degrees, whereas passive extension can reach up to 90 degrees. Both movements involve the metacarpo-phalangeal joints. (Kapandji, 1982)
Finger flexion and extension are important to practice because the hand is, as the effector organ of the upper limb, one of the most important parts of the body since it can perform many actions, fulfilling its own essential function; prehension. Adding individual finger and thumb movements to the rehabilitation program could eventually enable grips such as the pincet or pen grip. (Kapandji, 1982)
Figure 12 illustrates how the extension is performed.

Forearm pronation and supination

Pronation and supination (=pronosupination), also known as rotation, is the movement of the forearm about its longitudinal axis. The movement involves two joints, which are mechanically linked (Kapandji, 1982):

- the superior radio-ulnar (SRU) joint
- the inferior radio-ulnar (IRU) joint

Rotation around this longitudinal axis adds a third degree of freedom to the wrist, which enables the hand to be placed in any position to grasp or support an object, e.g., protecting and cleaning the body or holding a screwdriver. (Kapandji, 1982) This emphasises the importance of practising pronosupination during rehabilitation.

The position of **supination** is achieved when the palm is facing superiorly, and the thumb is pointing

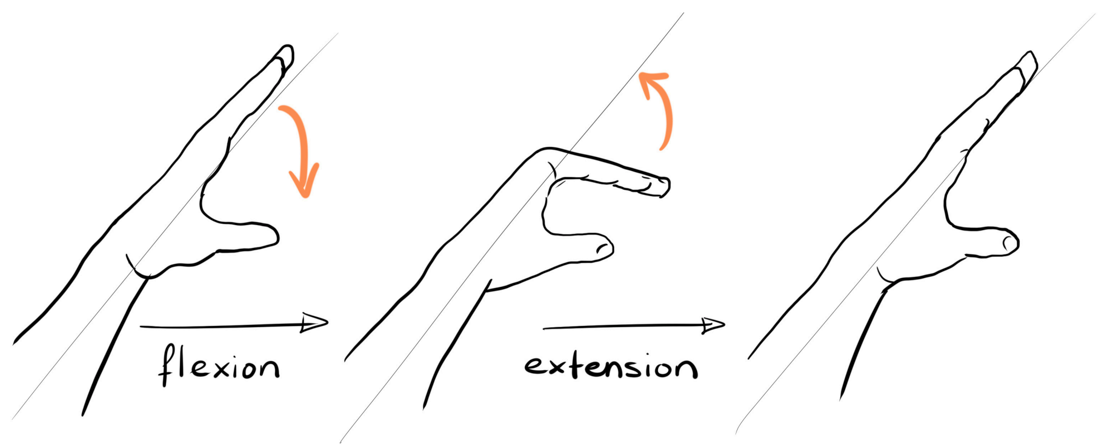


Figure 12. Flexion and extension of the fingers (adapted from Kapandji, 1982)

laterally. The range of motion from the neutral position to the supination position is 90 degrees. Figure 13 illustrates how supination is performed. The position of **pronation** is achieved when the palm is facing inferiorly, and the thumb is pointing medially. The range of motion from the neutral position to the position of pronation is 85 degrees. Figure 13 illustrates how pronation is performed. The range of true rotation of the forearm is thus about 180 degrees. When rotation of the shoulder would also be included, the range of motion can extend to 360 degrees.

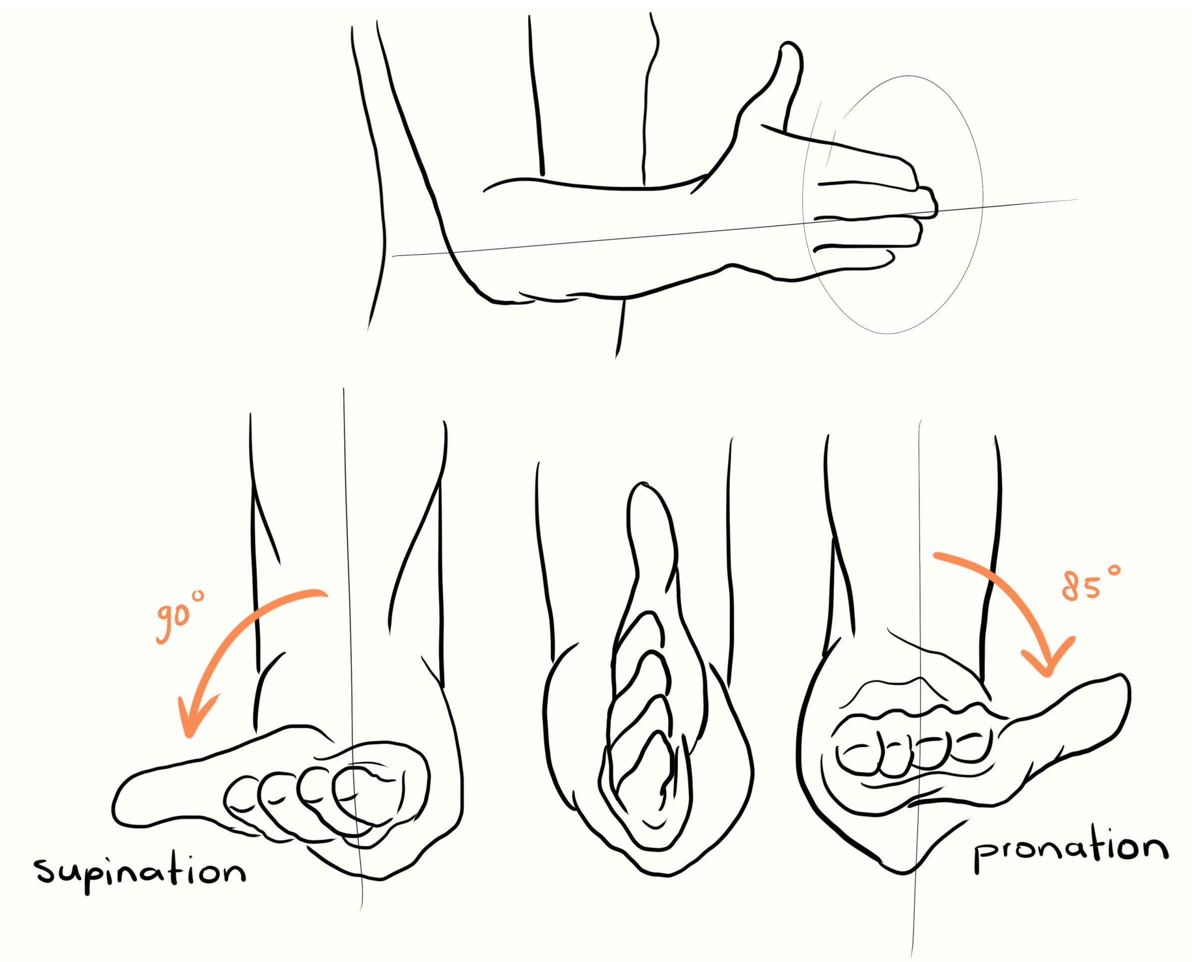


Figure 13. Pronosupination of the forearm (adapted from Kapandji, 1982)

Key insights

Because of the **neuroplasticity** of the brain, **the first three months** after a stroke incident **are crucial**. In these months, most improvements can be made. After that, improvements are still possible, but at a much slower pace.

Stroke recovery is **heterogeneous** in nature and varies for each stroke survivor. The starting point and improvement curve are different for each patient. Products can better be **designed for a specific level of physical abilities rather than for a certain period within the process**.

During the rehabilitation program, people generally spend approximately **fifty days in inpatient care** and spend **the months after in outpatient care**.

Extension movements in general are considered to be the **most important during upper-limb rehabilitation**. Finger extension is considered more important than finger flexion. And forearm supination is considered more important than forearm pronation.

Explore

2.3 Anatomy of the hand and forearm

2.3.1 Introduction

To understand what parts of the human body enable the movements that people after a stroke need to perform, this chapter looks at the anatomy (that studies the structure of body parts and their relations to each other) of the human hand and forearm, specifically diving into the involved bones, muscles and the nervous system.

2.3.2 Research questions

Main question:
What does the anatomy and physiology of the human hand and forearm look like and how does it affect the design of an upper limb rehabilitation device?

Sub questions:

> What does the anatomy of the hand and forearm look like in terms of *bones*?
> What does the anatomy of the hand and forearm look like in terms of *muscles*?
> What does the anatomy of the hand and forearm look like in terms of *the nervous system*?

2.3.3 Methods

Literature research: snowballing method

2.3.4 Bones

In Figure 14 the bones in the human hand, the effector extremity of the upper limb, can be seen. The upper three bones in each finger (except for the thumb, which has only three) are called the phalanges. The bones in the palm are called metacarpals and the bones in the wrist are called carpals. The phalanges, metacarpals, and carpals form the hand. The ulna and radius, which can be seen at the bottom of Figure 15, are part of the forearm.
As explained in Chapter 1.3, the hand trainer facilitates two movements.

(1) Hand **flexion/extension movement**: all bones in the fingers, palm, and wrist are used.

(2) For **forearm pronation/supination movement**: the ulna and radius are used. When performing pronation, the radius rotates over the ulna, whilst performing supination, the radius, and ulna are parallel to each other.

(Marieb & Hoehn, 2016)

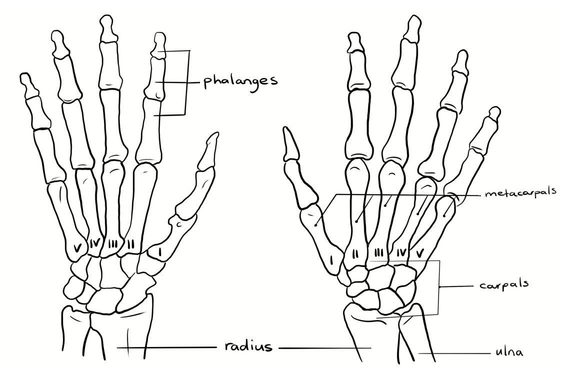


Figure 14. Bones in the human hand, left: anterior view, right: posterior view (adapted from Marieb & Hoehn, 2017)

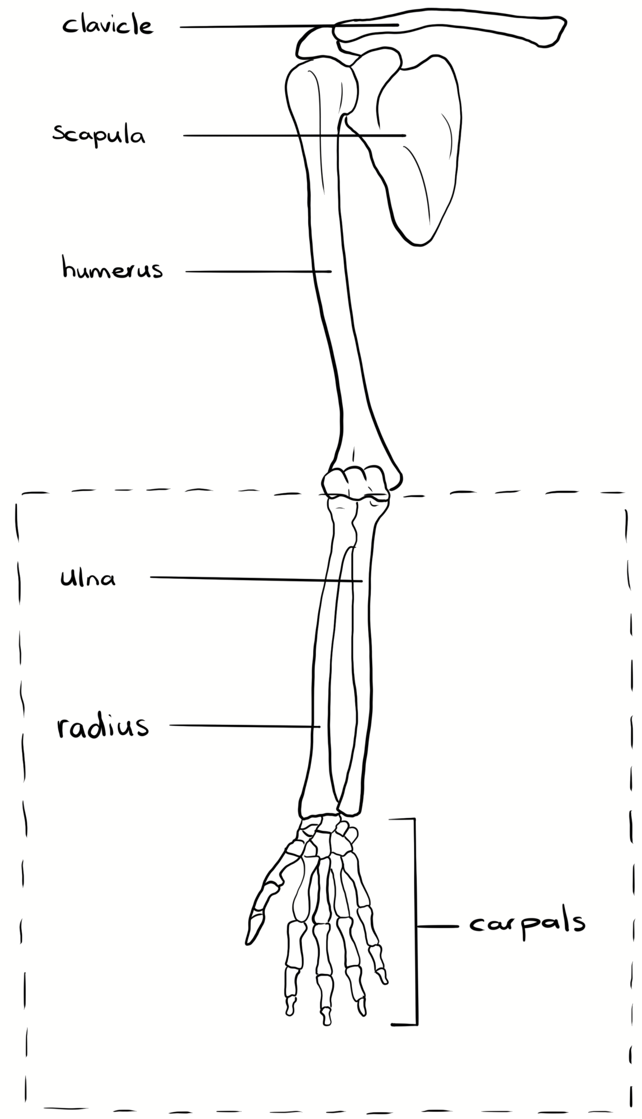


Figure 15. Bones in the human forearm, anterior view (adapted from Marieb & Hoehn, 2017)

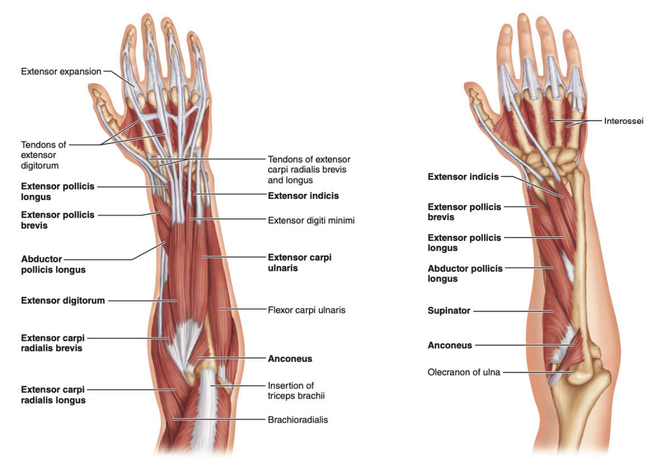


Figure 16. Muscles in the human forearm, posterior view, left: superficial muscles, right: deep muscles (adapted from Marieb & Hoehn, 2017)

2.3.5 Muscles

Figure 16 and Figure 17 give an overview of all the muscles that are present in the human hand and forearm, distinguishing muscles that lie in the first superficial layer and the second layer.

(1) For hand **flexion**, the following muscles are used:
flexor digitorum superficialis + flexor digitorum profundus + flexor pollicis longus (for the thumb only)

(2) For hand **extension**, the following muscles are used:
extensor digitorum + extensor pollicis longus and brevis (for the thumb only) + extensor inclicis (for the index finger only)

(3) For forearm **pronation**, the following muscles are used:
pronator teres + pronator quadratus

(4) For forearm **supination**, the following muscles are used:
supinator + biceps brachii

(Marieb & Hoehn, 2016)

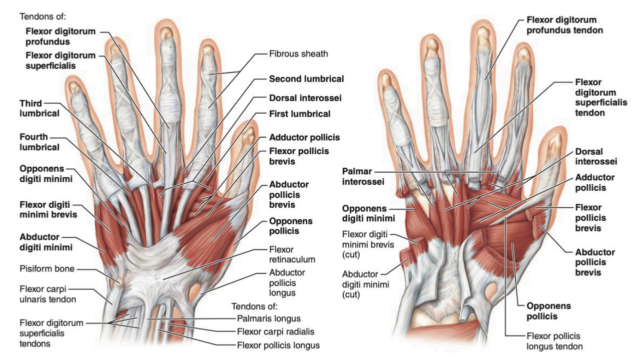


Figure 17. Muscles in the human hand, anterior view, left: superficial later, right: second layer (adapted from Marieb & Hoehn, 2017)

2.3.6 The nervous system

The nervous system of the human body has three main functions. The first one is **receiving sensory input**. The nervous system uses many sensory receptors, divided over the whole body, to monitor changes inside and outside the body. The second function is **integration**, the process of interpreting the input and deciding what reaction is suitable. The third function is **motor output**. The nervous system activates the muscles and glands of its organs to cause appropriate responses.
The central nervous system (CNS) consists of the brain and the spinal cord, whereas the peripheral nervous system (PNS) consists of all the cranial nerves, spinal nerves, and associated ganglia outside the CNS. The peripheral nerves accommodate communication from all parts of the body to the CNS and the other way around. The sensory subdivision of the PNS conducts impulses from the receptors to the CNS. The motor subdivision of the PNS conducts impulses from the CNS to the effectors, the muscles, and the glands. (Marieb & Hoehn, 2016)

After a stroke incident, the brain in the CNS does not receive messages correctly anymore. Due to a blockage or rupture in a blood vessel, blood cannot carry essential nutrients and oxygen to the brain anymore which damages or even destroys brain cells.
Since the brain does not understand sensations as well as it did before, patients may feel more pain than normal while doing regular activities or cannot regulate their body temperature. As was explained before, depending on the region of the brain that is damaged, the effects may be very different. (Goldman, 2019)

The hand trainer is currently designed to be used when the left hemisphere in the cerebrum of a patient's brain is damaged. This results in right-sided weakness or paralysis and sensory impairment. In this case, communication between the parts of the CNS and PNS that lie in the right hemisphere of the cerebrum is still possible.
However, as mentioned before, the neuroplasticity of the brain in the first three months after the incident gives the damaged nerves the ability to adjust and form new communication links to restore the communication between CNS and PNS.

Key insights

Almost all bones in the hand and forearm **are used during the two movements** that the hand trainer is accommodating: flexion/extension of the hand and pronation/supination of the forearm.

Six muscles in the hand are used for flexion/extension of the hand.

Four muscles in the hand and forearm are used for pronation/supination of the forearm.

After a stroke incident, **the brain cells are damaged or destroyed and do not receive messages correctly** anymore and sensations are out of balance. Patients most likely experience right- or left-sided weakness or paralysis and sensory impairment.

2.4 Market references

2.4.1 Introduction

Many devices already exist on the market focusing on limb rehabilitation. Specifically focusing on hand and forearm rehabilitation, the number is scaled down, but interesting devices can be observed. Some of them are publicly available and others are only used in rehabilitation clinics and not for home use. In this paragraph, rehabilitation devices for hand, finger, and forearm therapy are researched.

2.4.2 Research questions

Main question:
What opportunities and flaws can be found in upper limb rehabilitation devices that are currently on the market?

Sub questions:
> What types of devices focusing on hand and forearm rehabilitation are currently on the market?
> What movements do these devices facilitate?
> Which devices facilitate flexion/extension and what mechanisms are used for it?
> Which devices facilitate pronosupination and what mechanisms are used for it?
> What is working well for these devices?
> What is not working well for these devices?

2.4.3 Methods

Literature research: snowballing method
Interviews: semi-structured interviewing with a physical therapist and an occupational therapist (PT, personal communication, 2023) (OT, personal communication, 2023).
Observations at Rijndam Rehabilitation Center: shadowing, observing.

Figure 18. AMADEO (adapted from Tyromotion, 2022)

Finger and **hand therapy**
Movements: 1. individual finger flexion/extension, 2. wrist pronation/supination
++ usable for both hands, includes patients with spasticity, adjustable in height, the spread of fingers, and position of hand during pronosupination, passive/assistive and active modes
- - high costs, only used in clinics, not portable

Figure 19. Armeo Spring (adapted from Hocoma, 2022)

Finger and **hand therapy**
Movements: 1. finger flexion/extension, 2. wrist pronation/supination
++ individual finger and thumb movement, adjustable in the spread of finger movement and position of hand during pronosupination, two fixation points
- - not portable, high costs

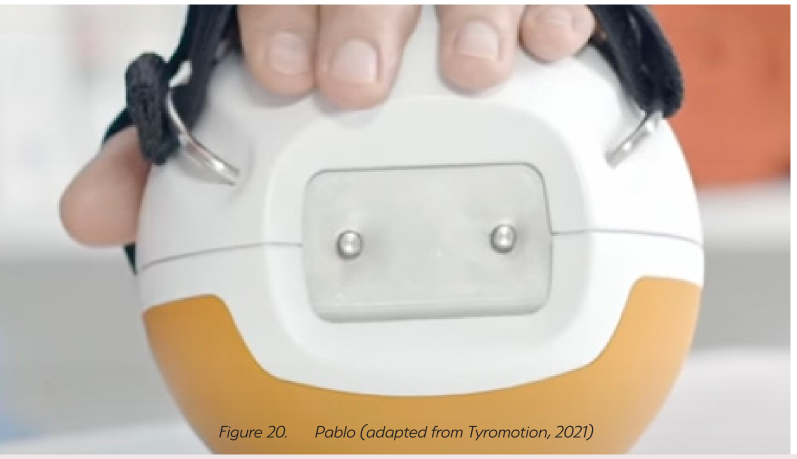


Figure 20. Pablo (adapted from Tyromotion, 2021)

Hand therapy
Movements: 1. wrist flexion/extension, 2. wrist pronation/supination
++ easy pronosupination movement, low costs, portable, intuitive and clear in use
- - little guidance in movements, low extrinsic motivation

Figure 21. FitMi (adapted from Flint Rehab, 2023)

Hand, arm, core and **leg therapy**
Movements: many
++ portable, intuitive and clear in use, simple, low costs
- - not suitable for early-stage rehabilitation, little guidance in movements


Figure 25. SaeboMAS (adapted from Saebo, 2023)

Shoulder and **arm therapy**
Movements: 1. shoulder adduction/abduction and circumduction, 2. arm flexion/extension, 3. forearm flexion/extension, 4. wrist pronation/supination
++ supports the weight of the arm to perform shoulder movements
- - portable, low costs, not for early-stage recovery

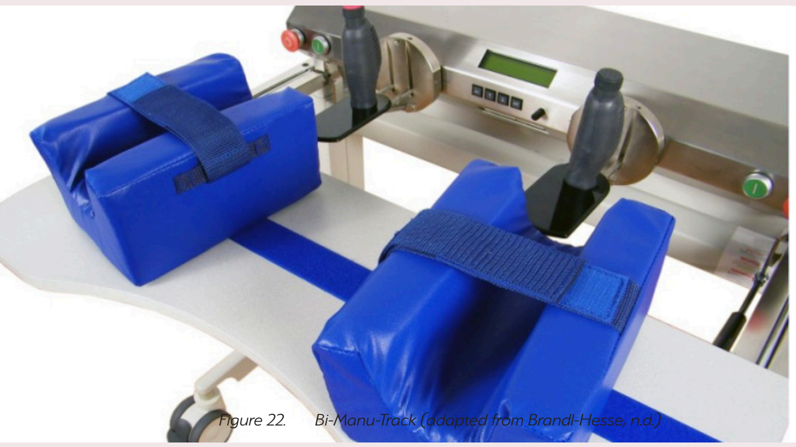


Figure 22. Bi-Manu-Track (adapted from Brandl-Hesse, n.d.)

Finger and **hand therapy**
Movements: 1. finger flexion/extension, 2. wrist pronation/supination, 3. wrist flexion/extension
++ spasticity taken into account, attention to both hands and forearms
- - bulky, high costs, stationary/not portable, limitation to x/y movements


Figure 23. InMotion (adapted from BIONIK, 2022)

Finger, hand and **arm therapy**
Movements: reach/grasp movements incl. 1. finger flexion/extension, 2. wrist pronation/supination
++ adjustable length of forearm rest, adjustable straps, smooth pronosupination, contoured finger and thumb grips, support under little finger
- - not portable, high costs

Figure 26. GripAble (adapted from GripAble, 2023)

Finger, hand and **arm therapy**
Movements: 1. finger flexion/extension, 2. wrist pronation/supination, 3. wrist flexion/extension, 4. wrist redial/ulnar deviation, 5. grip/release
++ two independent parts that can move separately, portable, low costs
- - no point of fixture, so good arm function required

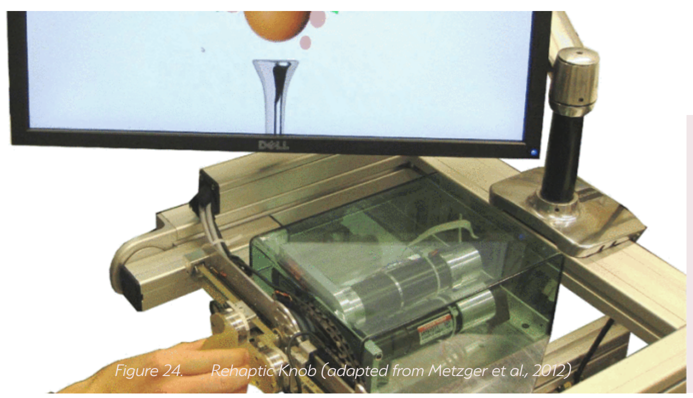


Figure 24. RehapticKnob (adapted from Metzger et al., 2012)

Finger and **hand therapy**
Movements: 1. finger flexion/extension, 2. wrist pronation/supination, 3. wrist flexion/extension
++ spasticity taken into account, attention to both hands and forearms
- - bulky, high costs, stationary/not portable, limitation to x/y movements

Key insights

Multiple support points on the forearm are often integrated into existing devices to increase the effectiveness of pronosupination movement. The ability to pronate/supinate the forearm independently from the shoulder needs to be considered.

Implementing **multiple movement exercises** is likely to **increase product costs**.

Simple and **easy-to-use products** tend to become **more portable** but also less diverse and **less advanced in movement possibilities**.

The adjustability of hand and finger position is favorable to achieve an ergonomic posture. Some devices prove that adjustability is possible. It does come with higher costs.

3 State of the art

This chapter dives into the state of the art of the development process of the portable hand trainer. This is presented by analyses of the working principles and the earlier performed usability study combined with findings from small-scale product tests with the researcher and fellow students. It concludes with an overview of the identified issues on the product within its system.

This chapter is structured in the following parts:

Explore

3.1 The working principles

The portable hand trainer

3.1.1 Introduction

The second iteration of the hand trainer, the starting point of this project, is shown in Figure 27 and Figure 28. The product is broken down to gain understanding of the mechanisms and electronics that enable the functionalities of the physical device. It is crucial to take the necessary components into account in the process of redesigning the embodiment of a product. This chapter presents the working principles of the hand trainer and provides an overview of the composition of all components.

Figure 27. Second iteration prototype of hand trainer

3.1.2 Research questions

Main question:
What are the functionalities of the current design of the hand trainer and how do they positively or negatively affect the rehabilitation process of people after a stroke?

Sub questions:
> What functions does the hand trainer currently have?
> What mechanisms are used for the functionalities?
> What flaws can be identified?

3.1.3 Methods

Breaking down device: trial and error
With little prior knowledge about the interior design of the device, trial and error can be defined as breaking down the device based on intuition and references. By multiple trials and errors to find the most efficient and harmless way of opening the device, the mechanisms and electronics in the interior design are examined.

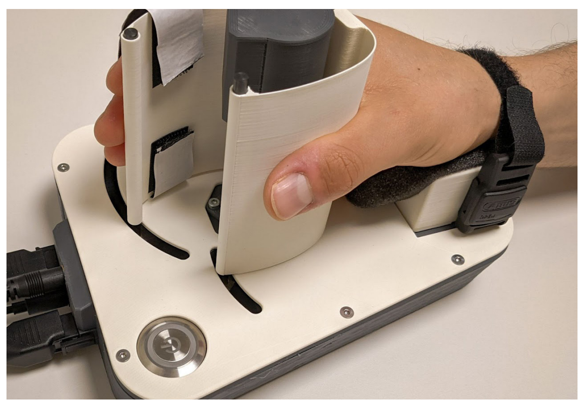


Figure 28. Second iteration prototype of hand trainer

3.1.4 Mechanisms and electronics

Four main mechanisms and/or electronic circuits are distinguished and explained in the next paragraphs.

1. Shell movement gears
The vertical shell on the top of the device is designed to perform **flexion and extension of the hand**, as shown in Figure 29 and Figure 30. The shell is driven by a mechanism inside the device. Two rods at the endpoints of the shell are connected to two lever arms. The lever arms transmit the movements to multiple gears (Figure 31 and Figure 32). One of the gears is connected to a motor, that can actuate the shell and decrease or increase the patient's effort to perform flexion and extension.

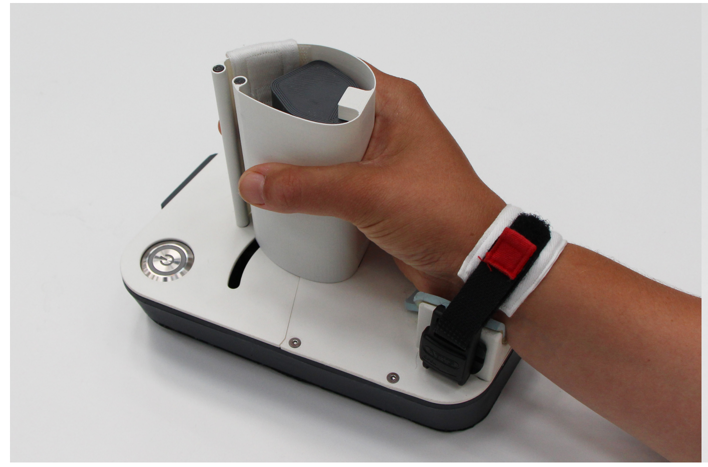


Figure 29. Performing flexion with the shell

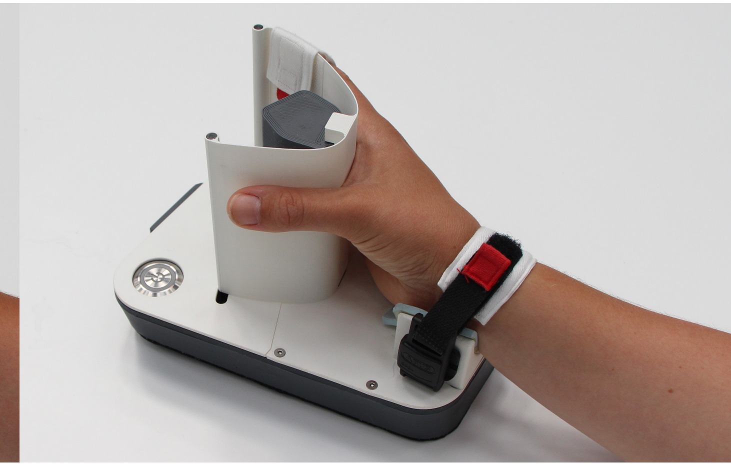


Figure 30. Performing extension using the shell

Figure 31. Shell movement gears, top view

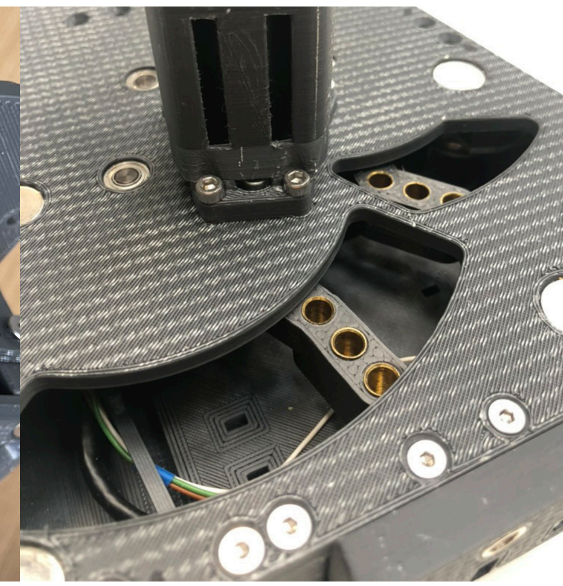
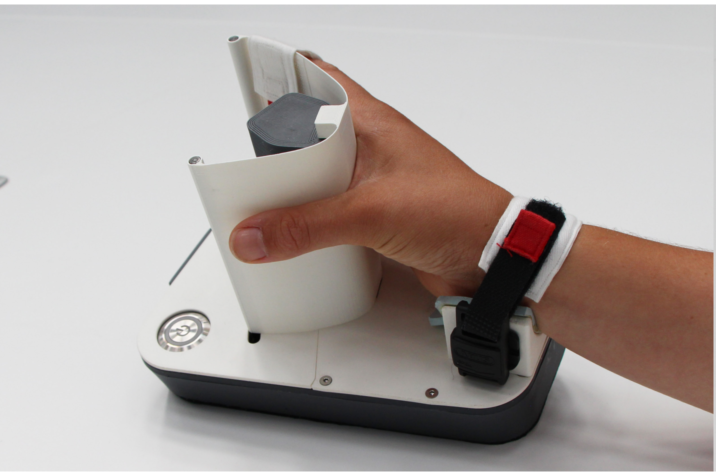


Figure 32. Shell movement gears, side view

2. Inertial Measurement Unit
The **pronosupination movement** is performed by tilting the device along the longitudinal axis of the forearm, demonstrated in Figure 33 and Figure 34. The rotational angle is captured by an inertial measurement unit (IMU), shown in Figure 35 and Figure 36, to allow navigation in the game. By performing pronation, the virtual hand is moving to the left and by performing supination, the virtual hand is moving to the right.



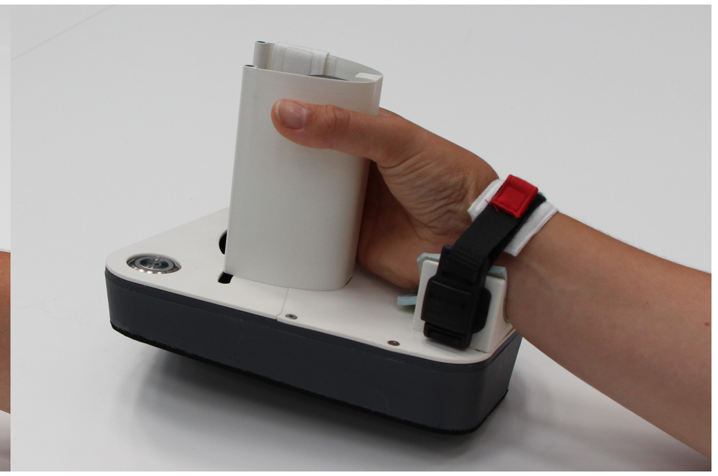
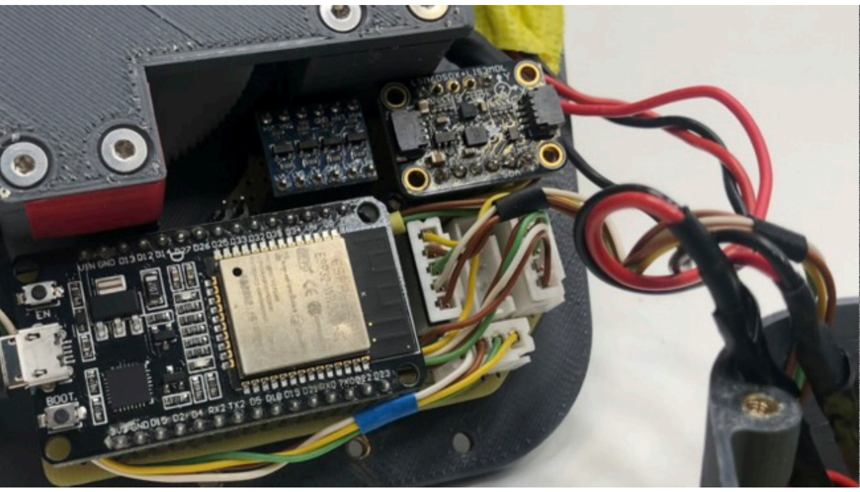


Figure 33. *Pronation movement with the device*

Figure 34. *Supination movement with the device*



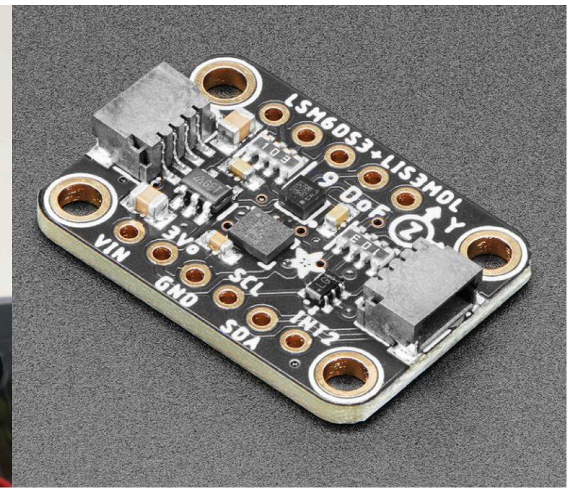


Figure 35. *IMU placement in the device*

Figure 36. *Inertial measurement unit (IMU) (adapted from Kiwi electronics, n.d.)*

3. On/off button

The button that is located in the left corner of the top cover of the device (Figure 37) has two functions: 1. **turning the device on and off** and 2. **navigating** through the introduction pages of the game. The button is enclosed in the cover of the device and connected on the inside to a microcontroller board, see Figure 38.

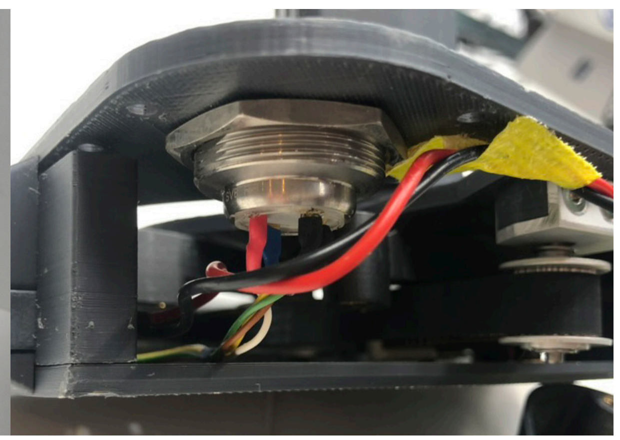
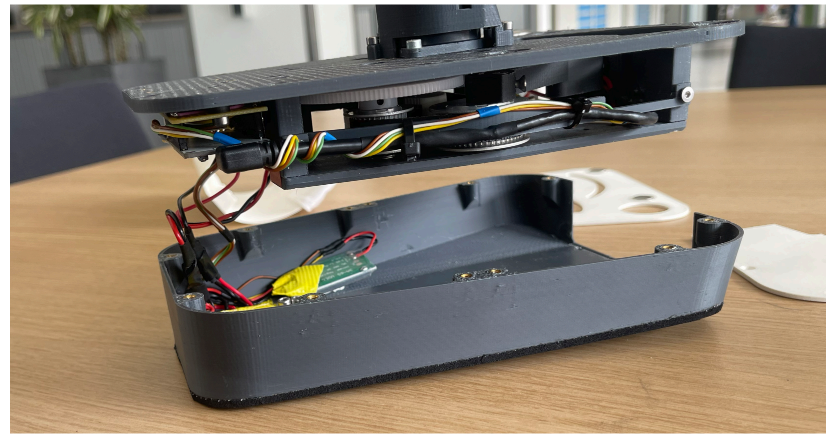


Figure 37. *On/off button placement on device*

Figure 38. *On/off button connection inside the device*

4. External cables

There are four outgoing cables for the **power supply**, **connection with a laptop** and two **emergency stop** buttons. These external cables are connected to the device through one central point, a connection block at the back of the device. A couple cables run through the body of the device to connect the block to the circuit boards at the back of the device, as can be seen in Figure 39 and Figure 40.



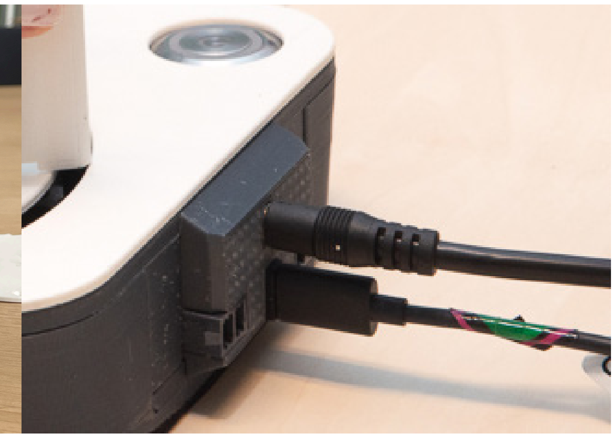


Figure 39. *External cables connection to circuit boards*

Figure 40. *External cables connection block*

Components overview

Overall, it can be concluded that the components take in the majority of the inner volume of the device, which leaves little room for additional components if that would be needed for the redesign. Redesigning the shape of the base and the composition of the components would be necessary in that case. Figure 41 gives an overview of the general dimensions of the hand trainer assembly. Figure 42 shows a section view of the device and Figure 43 gives a clear overview of the components in the interior.

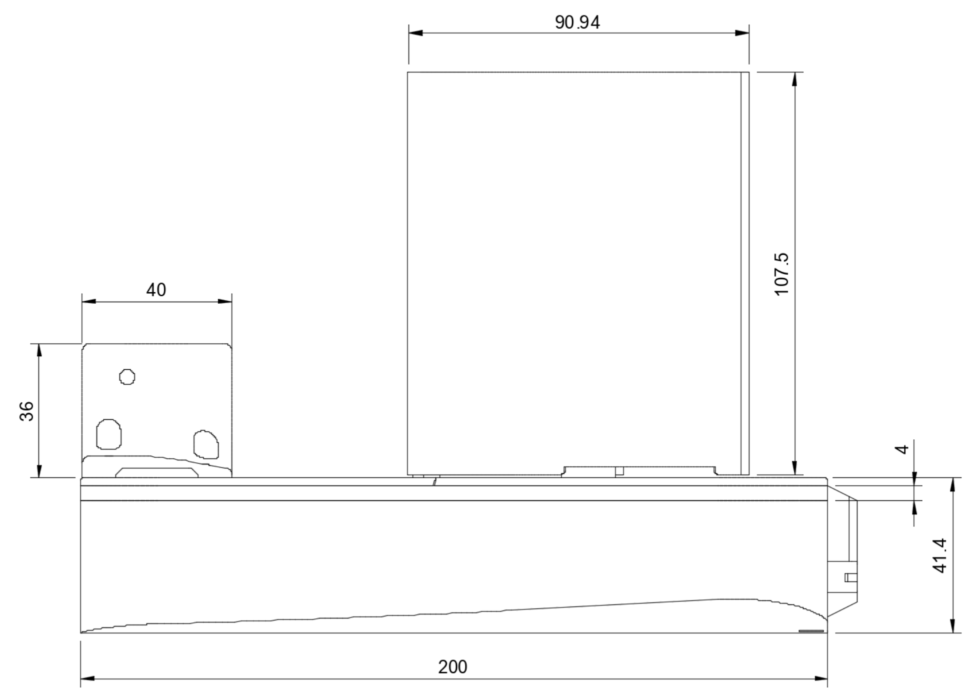


Figure 41. *General dimensions of the hand trainer assembly (in mm)*

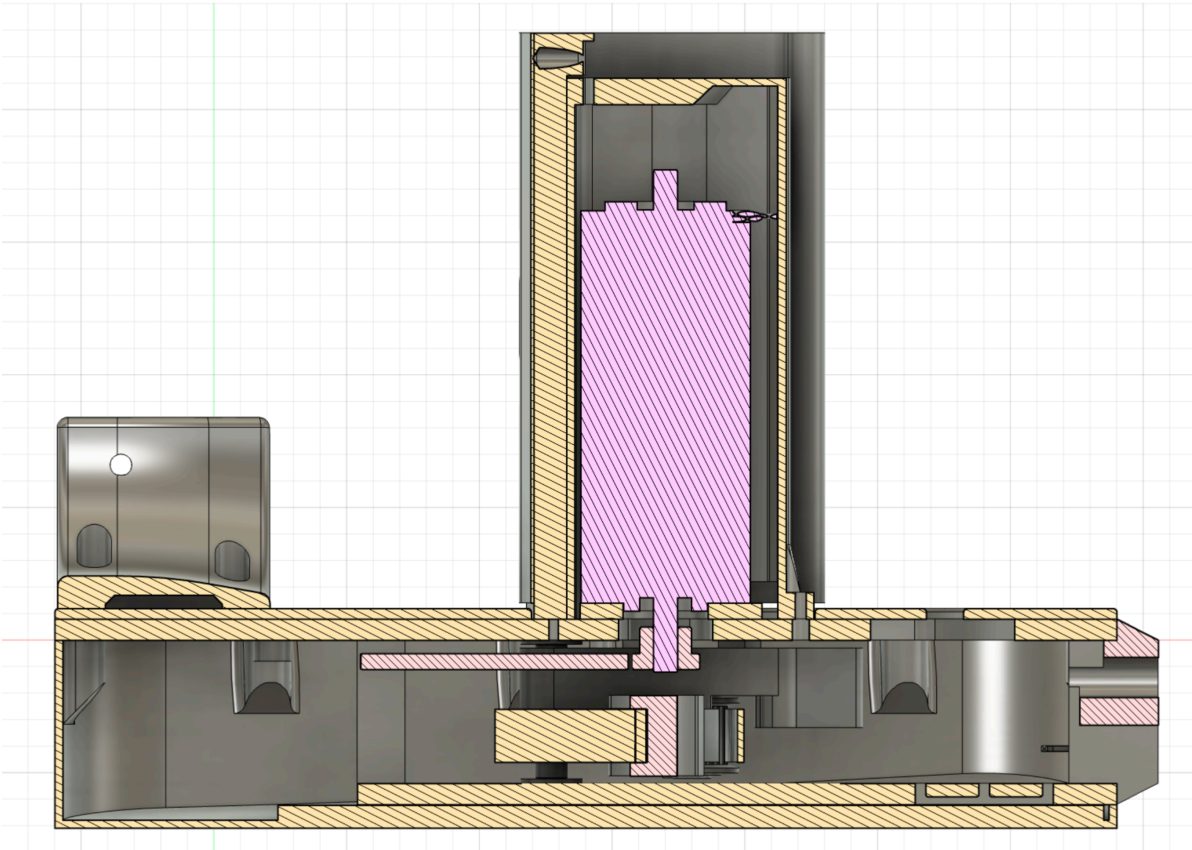


Figure 42. Section view of hand trainer assembly

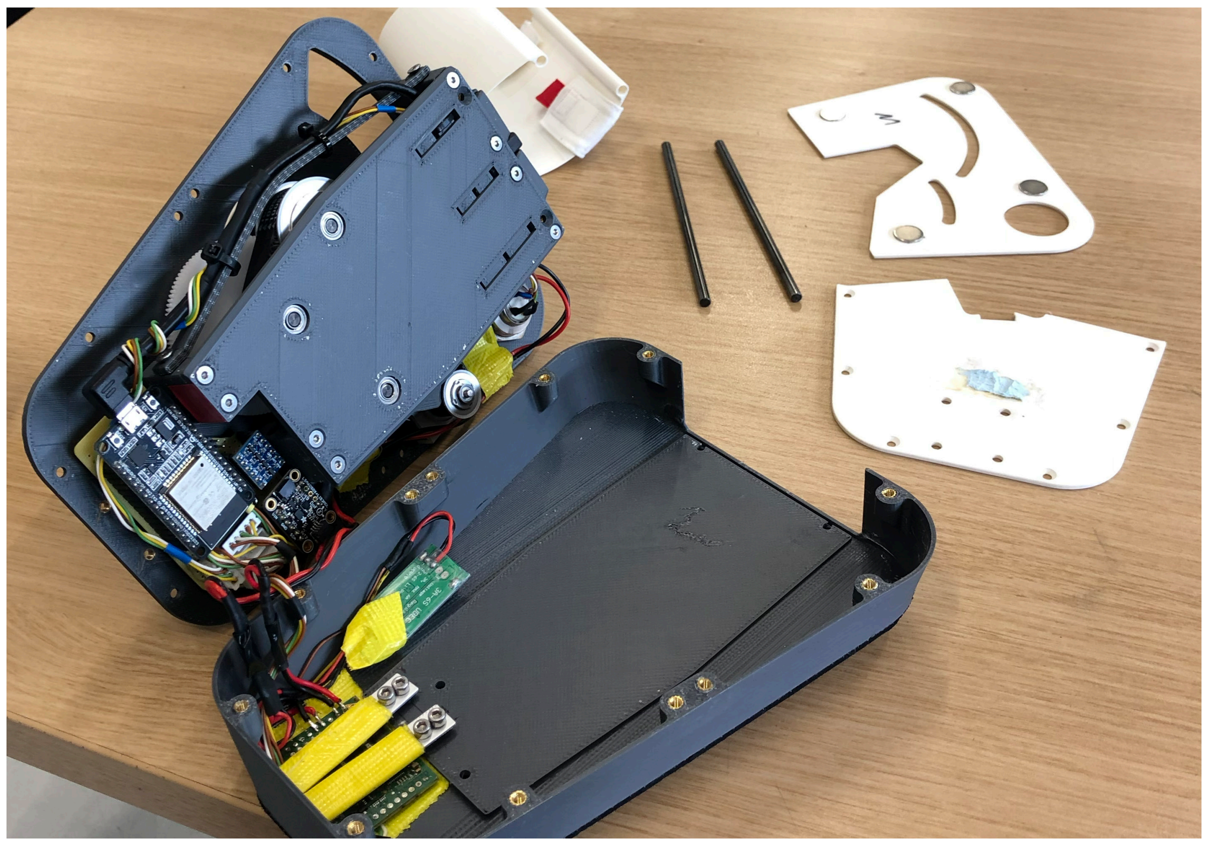


Figure 43. Overview of mechanics and electronics in the interior of the hand trainer

Key insights

The components in the device are efficiently organised which leaves **not much room** for additional mechanical or electronic components.

The **weight** of the device **cannot easily be reduced**, which has to be considered while redesigning the bottom part (the base).

Timewise, it would be wise to solely **change the base of the device according to the dimensions of the top cover**.

3.2 Usability study '22

Analysis of the usability study on the portable hand trainer in the Summer of 2022

3.2.1 Introduction

In the summer of 2022, a usability study on the second design iteration of the hand trainer has been conducted. The study is the motivation for this master thesis and this chapter provides an analysis of the results.
In order to manage the time constraints, a representative subset of the participants is selected for the analysis. The selection is done with care to ensure the data still represents a wide range of experiences and opinions.

Introduction to the study

The study's objective was to investigate the usability of the haptic hand and forearm training device. The study has been conducted with thirteen participants (ten healthy participants and three therapists).
In a single-session experiment, the participants were instructed (fifteen minutes) and asked to set up the hand-training device and perform exercises using a computer game in an unsupervised scenario (fifteen minutes). During the experiment, a video was recorded and the eye movements of the participants were tracked. Metrics such as the time to set up the device, the time to complete a task and the amount of technical errors were documented.

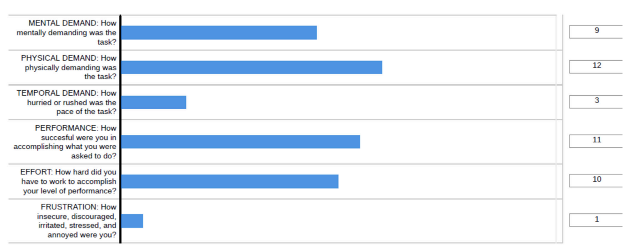


Figure 44. Result of NASA-TLX questionnaire rates on the device and the game (best readable in electronic format)

After the experiment, the participants were asked to fill out four usability questionnaires (NASA-TLX (Figure 44), IMI, PSSUQ and SUS) for a total of twenty-five minutes and provide feedback in a fifteen-minute semi-structured interview afterward.

3.2.2 Research questions

Main question:
What are the flaws of the current design in terms of the physical device, GUI, game design, and the complete system?

Sub questions:
- What are the current issues in terms of ergonomy?
- What are the current issues in terms of usability?
- What are the current issues in terms of functionality?
- What issues are foreseen if patients after a stroke incident would use the hand trainer?

3.2.3 Methods

Audio recordings: modified thematic analysis
Eye-tracking videos: modified thematic analysis

Introduction to thematic analysis

The analysis of the usability study is done with inspiration of the thematic analysis method described by Kiger and Varpio (2020). This method can be used to analyse qualitative data by identifying repeated patterns. The key steps are: data familiarization, identifying initial codes, searching for themes, reviewing and defining themes and data interpretation. (Kiger and Varpio, 2020)

Given the time constraints in this graduation project, a modified version of the Kiger and Varpio (2020) method is used. While the core principles of the thematic analysis are used, certain adjustments are made to accelerate the process.

Analysis of the video and audio recordings

For this project, analysis is only performed for a subset of the participants and only on the audio and video recordings and not on the other metrics and questionnaire results due to time constraints. After listening to the audio recordings and watching the eye-tracking videos, the data has been searched for themes (= a patterned response or meaning). When a certain issue on the system was present in the data of two or more participants, this theme was defined as an 'identified issue'. During the analysis, primairy focus was on searching themes on the physical device and the complete system rather than the GUI and the game.

Figure 45. Example of eye-tracking heatmap from usability study

3.2.4 Identified issues

The issues that were identified by analysing the usability study results are marked with an orange-colored dot ● in Figure 47 on page 46. The issues are divided on the physical device, the GUI, the game. and the complete system.

Key insights

Inclusion and exclusion of people must be based on their hand and forearm functionality rather than their stage in the rehabilitation process.

The participants experience **unclear and insufficient guidance** on how to perform the pronosupination movement.

The participants experience **insufficient to no feedback on how to place the fingers and the wrist on the device**.

Performing **extension is usually difficult** for patients that still have little hand function.

While performing flexion and extension of the hand, **the thumb is not cooperating as much as the fingers**. The individual fingers are also not used equally.

Including independent movement of fingers and thumb could be an interesting feature to add.

To engage the patients in the long term, **more variations in the game design** are necessary. To engage the patients in the short term, **more connection to activities of daily life** (ADL) is envisioned.

The introduction pages are experienced as an information overload. **The cognitive load of reading instructions** prior to performing certain tasks could be too much for stroke patients.

Explore

3.3 Self-testing and peer testing

3.3.1 Introduction

Self-testing is performed to gain a more in-depth understanding of the product and how it operates in the system. Accordingly, the identified flaws and opportunities of the current design are presented in Chapter 3.4. Good to note is that the researcher was already introduced to the product before performing the self-test.

Peer testing is performed to get a non-biased Industrial Design perspective on the product, in addition to the thirteen participants from the usability study in 2022 (Chapter 3.2). Since this and future research involve humans, the HREC application was done and approved by the corresponding committee of the TU Delft. The HREC approval can be found in Appendix B.
The Informed Consent Form, the peer test protocol, and transcriptions of the audio recordings can respectively be found in Appendix C, D1 and D2.

3.3.2 Research questions

Main question:
What are the flaws of the current design in terms of the physical device, GUI, game design, and the complete system?

Sub questions:
- What are the current issues in terms of ergonomy?
- What are the current issues in terms of usability?
- What are the current issues in terms of functionality?
- What issues are foreseen if patients after a stroke incident would use the hand trainer?

3.3.3 Methods

Self-testing: cognitive walk-through (Interaction Design Foundation, 2023) and perspective-based inspection (Wilson, 2011).
Peer testing: concurrent thinking aloud, concurrent probing, semi-structured interview.

Self-testing (n=1) procedure:
During a 10-minute test, the instruction pages were followed, and the game was played by the researcher afterward. The cognitive walk-through method was used by performing the specific tasks that were described in the instruction pages. Simultaneously, the researcher was evaluating the usability of the device by adopting a certain perspective, in this case, a partially physically disabled person (perspective-based inspection). After the test, the insights were written down.

Peer testing (n=3) procedure:
The peer test was conducted with three Industrial Design master students. The researcher asked the participant to use the device in a simulated unsupervised scenario (the researcher was always present), to turn it on, and to perform tasks in a game that is displayed on a laptop. The participants received instructions before the experiment. After the experiment, the participants were asked to share their feedback in a semi-structured interview. During the experiment, audio was recorded.
The setup of the experiment can be seen in Figure 46.

Figure 46. Peer tests set-up

3.3.4 Identified issues

The issues that were identified during the self-test are marked with a dark blue-colored dot ● in Figure 47 on page 46. The issues that were identified during the peer tests are marked with a purple-grey-colored dot ● in Figure 47. Some of the issues overlap with issues found in the usability study discussed in the previous chapter, some add on to found issues or are completely new. The issues are divided on the physical device, the GUI, the game. and the complete system.

Key insights

All three participants **did not understand how to use the wristband** correctly without extra explanation.

The participants experienced a **lack of support under the wrist** since the support is currently placed at an uncomfortable spot on the wrist.

All three participants experienced **tilting the device as unnatural** and felt a lack of assistance.

The instruction pages were experienced as **an information overload** without clear order of steps to take. Visualisations are favoured over text.

The participants emphasised that they **do not receive sufficient feedback** on whether they have their hand and wrist placed correctly and perform the movements right.

There is an **unequal exerting force distribution between the individual fingers** and **between the fingers and the thumb**.

The layouts/appearances of the GUI, the game design and the product **do no match** appealingly.

3.4 Identified issues

Insights from the context analysis, the usability study '22, self-testing, peer testing and observations at Rijndam

3.4.1 Introduction

This chapter combines and summarises the findings from chapters 2.1-3.3. The created map is used in the next chapter, the start of the defining phase, to create a concrete, prioritised list of improvements for the hand trainer.

3.4.2 Identified issues

A map has been created in which all the identified issues are mapped out (Figure 47). The issues are based on findings from the context analysis ○, the analysis of the usability study '22 ●, the performed self-test ● and peer tests ●, and informal interviews and observations at Rijndam Rehabilitation Center ○, discussed in chapters 2 and 3. Distinguished by colors, the issues can be categorised into four groups: **the physical device** (yellow), **the game** (light pink), **the graphical user interface** (orange), and **the complete system** (grey). Since the goal and scope of this graduation project is to improve the physical device, the highest priority was given to identifying issues in this category.

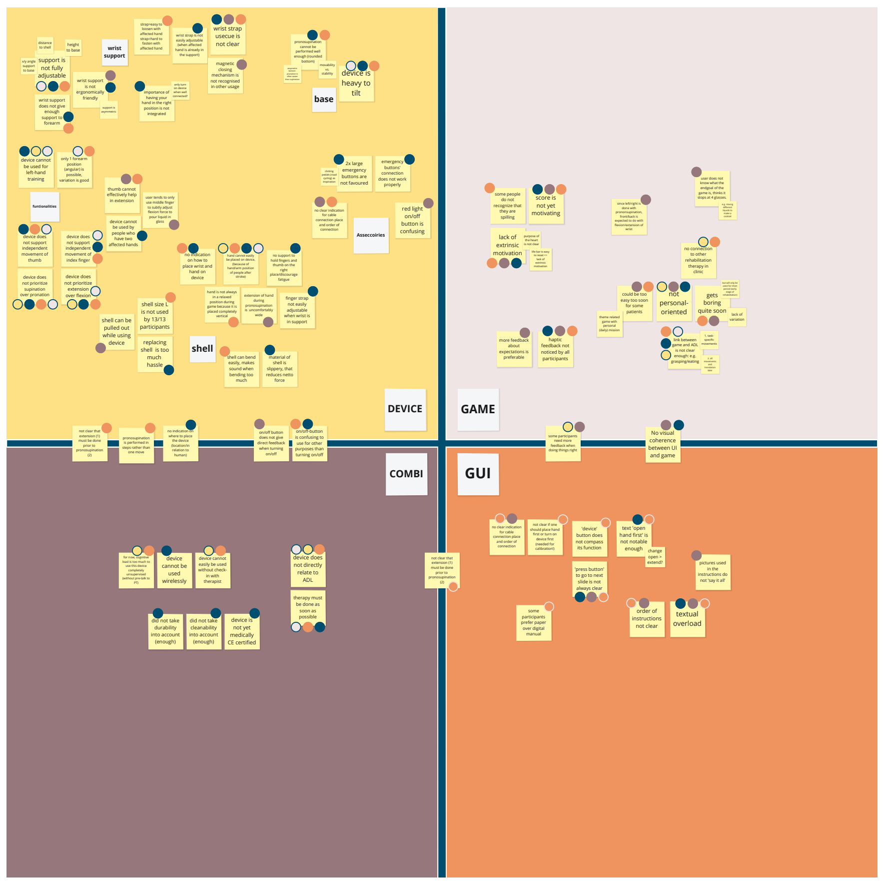


Figure 47. Map of identified issues (best readable in electronic format)

Figure 48. The main components of the physical device

Figure 49. Overview of the complete system

4 Design scope

This chapter connects the findings from the explorative phase to the defining phase, by shaping the target group and the stakeholders to create a design scope.
Defining a design scope is a crucial step in the design process because it establishes the project's focus, direction and boundaries.

This chapter is structured in the following parts:

4.1 The target group

Ischemic and hemorrhagic stroke patients

4.1.1 Introduction

Chapter 4.1 defines the characteristics of the target group that is designed for. The target group is the people that will be using the hand trainer, defined in a set of bullet points on exclusion and inclusion. This chapter also illustrates the context in which the product will be used.

4.1.2 The target group

Before this graduation project started, the target group was set to stroke patients that need rehabilitation in their affected hand and forearm. A condition was that the other, unaffected hand and forearm could be used to assist the affected side to put on the device and start the game. The product was specifically designed for right hand-usage since it is still in the developing phase.

For this project, the **target group** has been revised to:

> people who had an ischemic or hemorrhagic stroke incident
- are paralysed on the right side of the body
- also suffer from cognitive effects

> need inpatient rehabilitation in their hand and forearm
> have spasticity level 0,1, 1+ or 2*
> are in Brunnstrom (FMA) stage II - IV**
> any gender
> age is 18+

* The level of **spasticity** is usually rated from 0-4, using the Modified Ashworth Scale (MAS) or Tardieu Scale (Meetinstrumenten in de zorg, 2019). In a **talk with a physical therapist** from Rijndam, where the MAS method is used to rate spasticity, it is concluded that the product cannot be used by patients with spasticity levels 3 or 4, because the muscles in the hand and forearm will be too tensed and cramped up (PT, personal communication, 2023).

** The Brunnstrom Fugl-Meyer Assessment (BFM/FMA) is an assessment tool to measure, amongst others, the motor functioning, balance and sensation of stroke patients. Accordingly, patients are classified into six stages of Brunnstrom, I-VI. In a **talk with a therapist** from Rijndam, it was concluded that stage I is excluded because it includes patients who cannot yet experience reflexes. Stage V and VI are also excluded. Patients in these stages have almost regular mobility and tone and need more challenging practises focusing on more fine motor skills. (Meetinstrumenten in de zorg, 2021)

4.1.3 Context of use

The second iteration of the hand trainer (Figure 27 and Figure 28) was intended to be used minimally-supervised, in the inpatient or outpatient clinic, either on a table or in bed.

For this project, the **context of use** has been revised to:

> in an inpatient or outpatient clinic, outside therapy hours
> with minimal supervision (explanation on product use is given by a therapist, usage is solely done by the patient)
> in a position at which the patient's elbow can rest on a solid, rigid surface
> in a position at which the product and patient's elbow are at the same height

The context of use is visualised in Figure 51 on page 52.

4.2 The stakeholders

Individuals, groups and organisations that have interest in the hand trainer

4.2.1 Introduction

This chapter presents an analysis of the stakeholders that are involved in the development of the hand trainer. It is essential to consider the needs and expectations of stakeholders during the development of a new medical device.

4.2.2 The stakeholders

Stakeholders are individuals, groups or organisations who have, in any way, interest in the end-product, thus the portable hand trainer for upper limb rehabilitation. They are directly or indirectly affected by the outcomes, decisions and actions during the development and implementation of the product and are mapped out in a stakeholder map. It is important to consider the positive and/or negative influence they have on the product or the product has on them, and consider this while redesigning the hand trainer.

Figure 50 shows the stakeholder map in which all stakeholders are circularly mapped out in order of influence. Closest to the center are the stakeholders that have the highest influence on or by the hand trainer. In this project, the rehabilitation team is closest to the stroke patient, since they need to work with the product too, but are not the direct user. The patient's family and friends but also other patients at Rijndam often assist the stroke patient and therefore also have a rather high influence on or by the product. Stakeholders that have rather low influence on or by the product are e.g., the insurance company, the producers and the rehabilitation centers since they can limit or expand development and production possibilities.

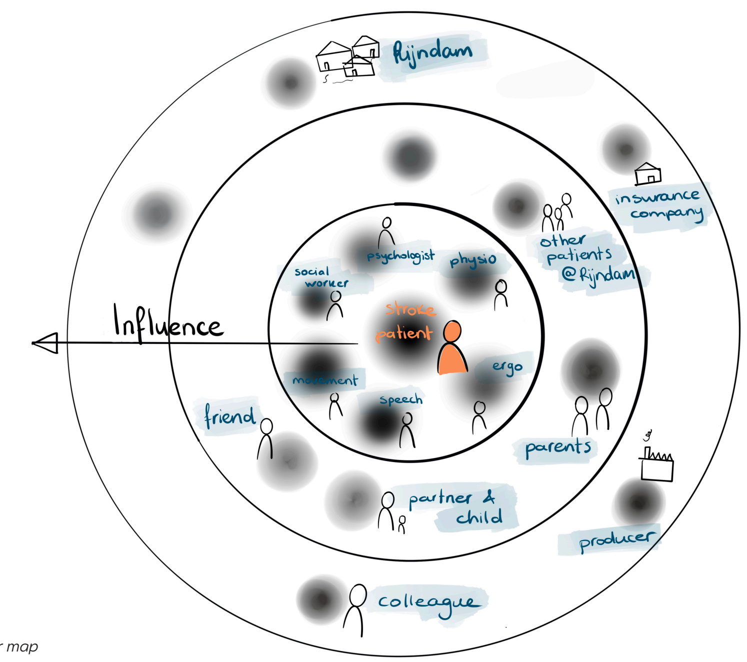


Figure 50. Stakeholder map

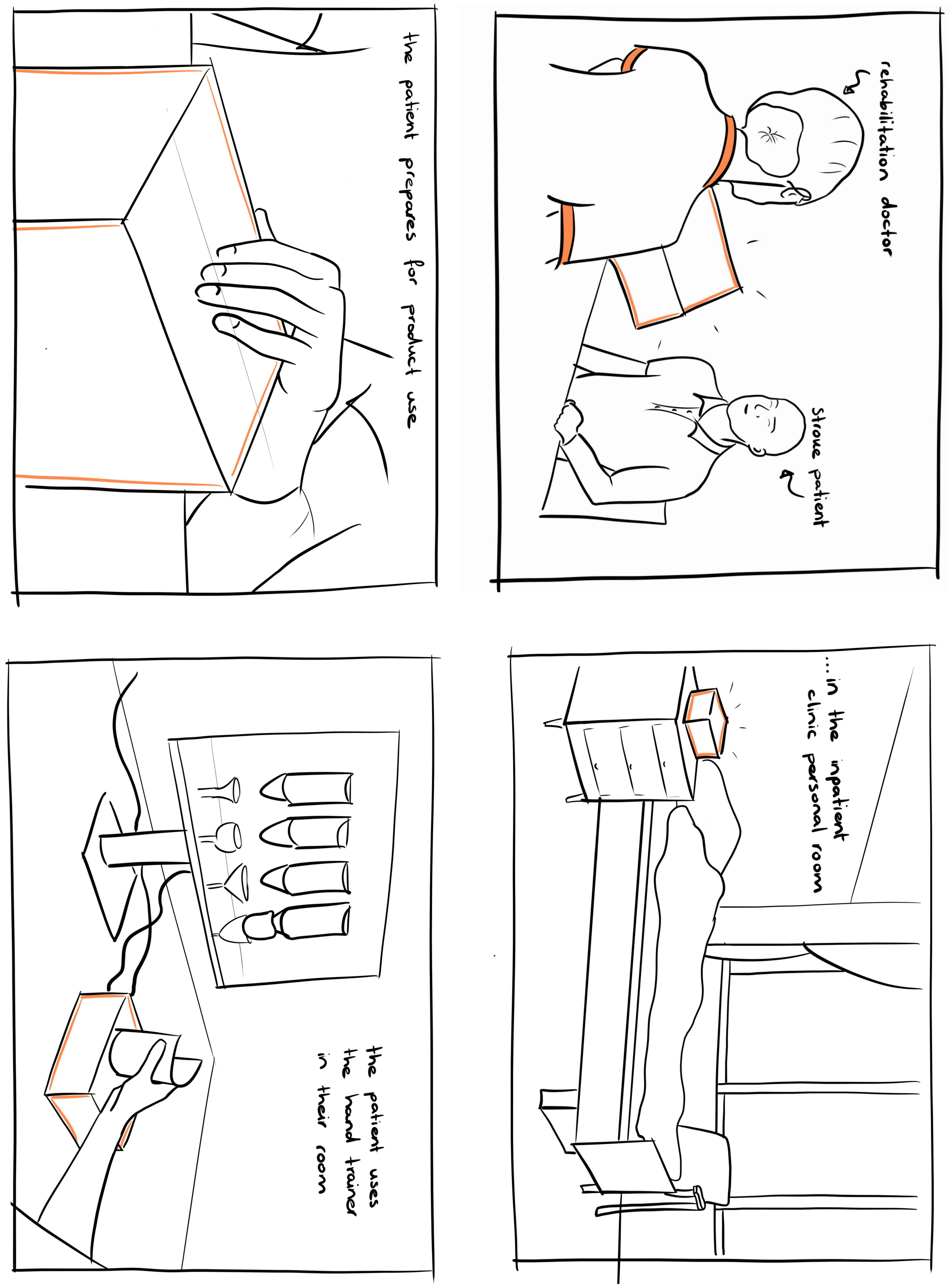


Figure 51. *Use scenario of the portable hand trainer*

4.3 Scope

Boundaries of the project in a framework

4.3.1 Introduction
This chapter describes the scope of the project by pointing out what is included and excluded to sketch the boundaries of the project. The decision matrix introduced in the next chapter and the list of requirements described afterward, are directly influenced by the defined scope.

4.3.2 The scope
The scope of a project sketches the boundaries of the project and provides a framework for the project planning and execution to ensure the intended outcomes are met.
Figure 52 illustrates the scope of this graduation project, in which the dark blue dotted lines represent the boundaries.

4.3.3 Excluded from the scope
Since this graduation project is limited to a duration of one hundred days and is dependent on the skills and resources of the researcher, some aspects of the development of the hand trainer are excluded from the scope:

- improvements in the game design
- improvements in the graphical user interface
- a formal usability study on the redesign with stroke patients in inpatient or outpatient clinics.

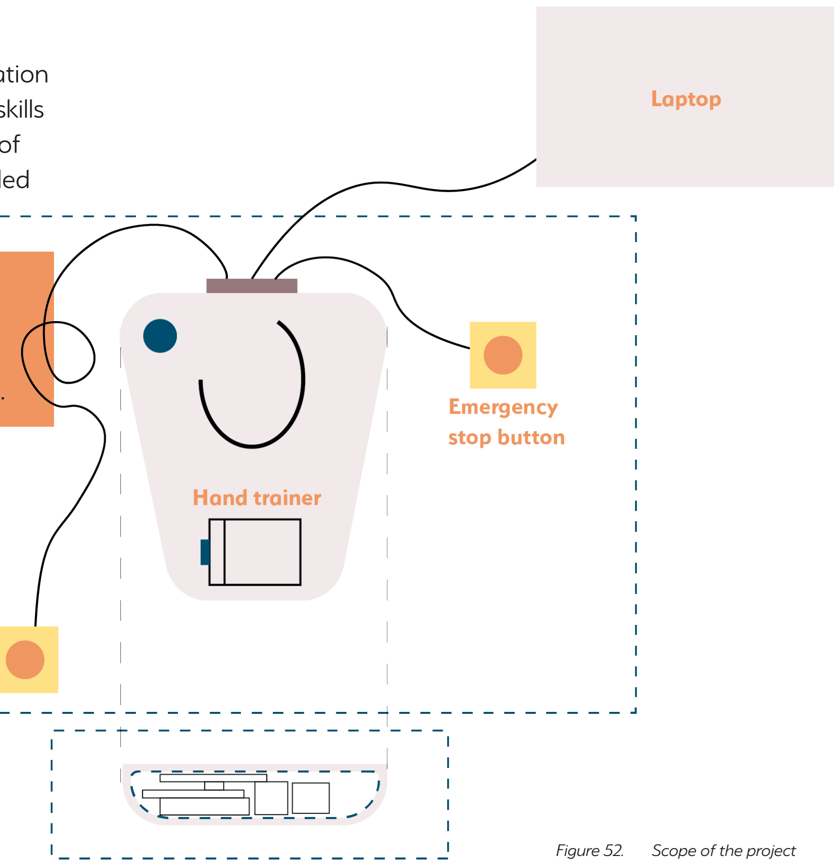


Figure 52. Scope of the project

4.4 List of improvements

4.4.1 Introduction
To translate the identified issues (Figure 47) into a concrete list of potential improvements on the current design, the issues are clustered (Figure 54). This resulted in eleven potential improvements on the device, five on the game, two on the GUI, and five on the complete system. This overview is **the foundation for the further development of the hand trainer**.

4.4.2 Decision matrix
Since time is limited in this graduation project, it was decided to prioritise the list of improvements and categorize them in high-priority, medium-priority and low-priority improvements. In this graduation project, **the high-priority and medium-priority will be addressed**. The low-priority improvements are outside the scope of this project.

The improvements are rated on four factors; effort, costs, added value, and sustainable impact, as can be seen in Figure 53. A weight factor is assigned to each of the four. The added value of the improvement is decided to be the most important, followed by the effort it takes to redesign, the costs accompanied by the improvement, and the sustainable impact it has on the existing design.

First, factors were **rated by the researcher**. To verify the decisions, the ratings were **discussed with a physical and occupational therapist and adjusted accordingly** (PT and OT, personal communication, 2023). Several iterations of the decision matrix can be found in Appendix E1.

	1 t/m5	5=much	5=high	5=much	5=positive	
	Factor	Effort	Costs	Added value	Sustainable impact	Score
	Weight factor	4	3	5	2	
device	Improve effectiveness pronosupination movement	2	1	5	3	**55**
device	Improve ease of use of wrist support & wrist strap	1	1	4	3	**54**
device	Improve donning/doffing of the shell and straps	3	2	5	3	**48**
device	Improve ergonomics of wrist support & wrist strap	2	2	4	3	**47**
device	Improve on/off button functionality	1	1	2	3	**44**
device	Redesign emergency buttons functionality	2	2	2	4	**39**
device	Improve finger placement and ergonomics of the shell	3	2	3	3	**38**
device	Improve connection of cables	4	1	2	4	**34**
device	Accommodate adjustable positioning of the wrist support	3	2	2	3	**33**
device	Include left hand usage	5	4	5	2	**32**
device	Include independent movement of fingers	4	3	3	2	**29**
game	Increase short-term engagement (extrinsic motivation)	2	2	4	3	**47**
game	Improve visual/audio feedback during game	2	1	3	3	**45**
game	Improve haptic feedback	4	1	4	3	**42**
game	Increase long-term engagement	4	3	5	3	**41**
game	Improve engagement with clinic therapy	2	1	2	3	**40**
GUI	Improve order of steps to take	2	1	5	3	**55**
GUI	Redesign instructions visuals that take the lead over text	3	1	4	3	**46**
combi	Improve cleanability	2	1	4	4	**52**
combi	Improve sustainability	2	2	4	5	**51**
combi	Wirelessness of device	4	2	5	4	**46**
combi	Usage without prior instructions from therapist	1	1	2	3	**44**
combi	Improve coherency between design of software and embodiment	3	3	2	3	**30**

Effort = time and complexity of implementing the improvement
Costs = costs of implementing the improvement
Added value = how much more valuable the end-product would be with the improvement
Sust. impact = an increase or decrease in sustainability of the end-product after implementing the improvement

High-priority
Medium-priority
Low-priority

Figure 53. Decision matrix on potential improvements

4.4.3 High-priority improvements
The potential improvements that have high-priority based on the decision matrix are:

The device
> Improve unnatural feeling of the pronosupination movement
> Improve the ease of use of the wrist support and wrist strap
> Improve the donning/doffing of the shell and strap
> Improve the ergonomics of the wrist support and wrist strap

4.4.4 Medium-priority improvements
The potential improvements that have medium-priority based on the decision matrix are:

The device
> Improve the on/off button functionality
> Redesign the functionality of the emergency buttons
> Improve the finger placement and ergonomics of the shell

The complete system
> Improve the cleanability of the device
> Improve the sustainability of the device

A detailed explanation of the improvements listed above can be found in Appendix E2.

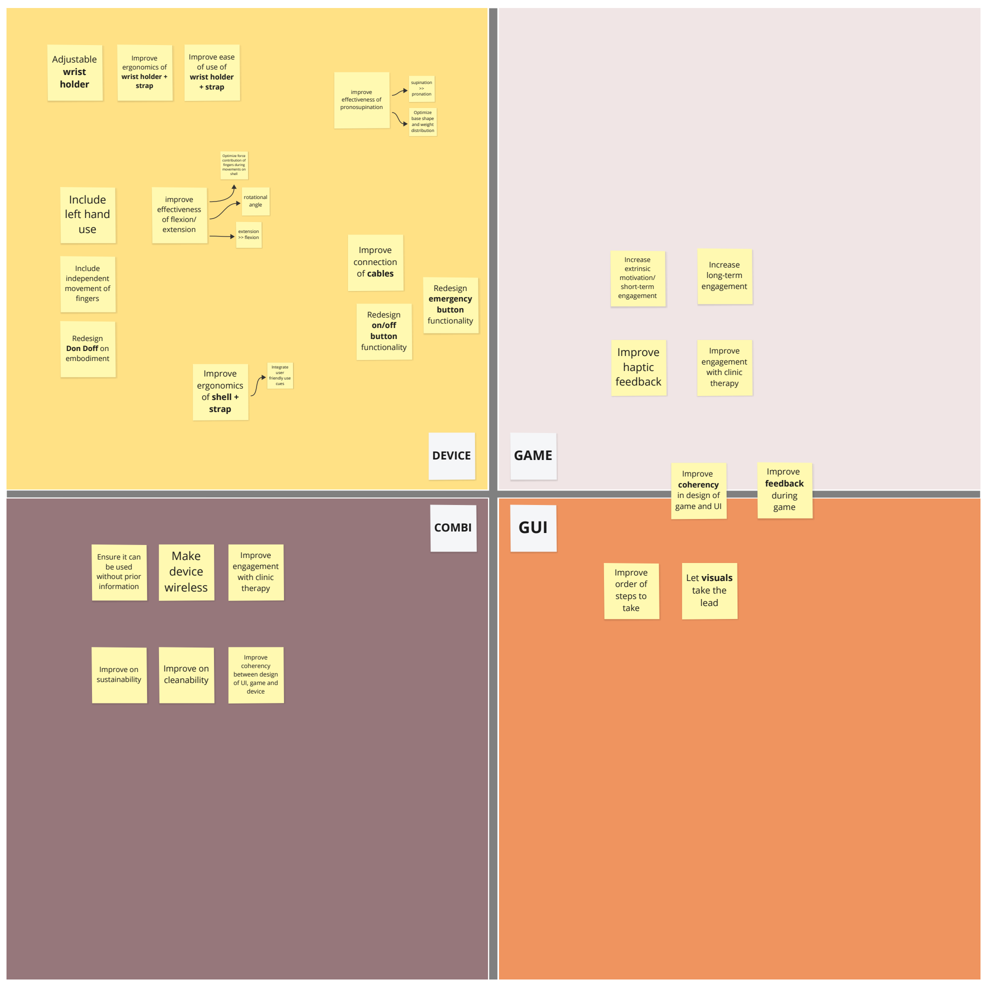


Figure 54. Clustered identified issues (best readable in electronic format)

4.5 List of requirements

4.5.1 Introduction
This chapter presents a list of requirements and wishes for the redesign of the hand trainer. The requirements and wishes are used to evaluate whether certain proposals and ideas are suitable for the given problem in the given context of use.

4.5.2 List of requirements
Requirements are statements about the product that **must be met**. The list is generated from the context analysis, the state-of-the-art analysis and the list of improvements.

The product must ...

> be used by stroke patients who are paralysed on the right side of their body
> be used by stroke patients that are in Brunnstrom (FMA) stage II-IV
> be used by stroke patients with a spasticity level of 0,1, 1+ or 2 according to the MAS scale
> facilitate donning and doffing by stroke patients in the above-mentioned criteria
> be used by stroke patients independently, but with minimal supervision of a therapist
> fit hand and wrist sizes of male and female adults from 18-85 y/o using P10-P90
> be used approximately 30 minutes per day, 7 days per week
> meet CE certification regulations for medical devices
> be easily transferable from the rehabilitation clinic to a person's home with assistance
> be used in inpatient and outpatient care of the rehabilitation process
> show improvement in the rehabilitation process of the patient
> fit within the rehabilitation program of stroke patients

4.5.3 List of wishes
Wishes are statements about the product that **would be valuable to meet** but are often not measurable.

The product should ...

> be easily transformable to a left-handed training device
> be used by stroke patients with spasticity levels 3 or 4 according to the MAS scale
> have as low production costs as possible
> be as durable as possible
> be as sustainable as possible
> be as easily cleanable as possible
> be as lightweight as possible

5 Concept development

This chapter presents the developing phase of the design process. Divided into two design cycles, the identified problems are tackled to create promising improvements to the current design. The ideas are iterated multiple times through testing and discussions with experts and peers. Chapter 6 subsequently translates the ideas into a feasible and viable final concept.

This chapter is structured in the following parts:

Develop

5.1 Approach

Developing an improved product design

5.1.1 Introduction

To give the rather non-linear and unpredictable developing phase structure, the approach to tackle the identified improvements is introduced in this chapter.

5.1.2 Approach

The approach is divided into two cycles.
The high-priority improvements are addressed first, in **cycle 1**. These improvements take rather low effort and/or have high added value. The medium-priority improvements are tackled afterward, in **cycle 2** since they have less added value and/or take more effort. The outcomes of the two cycles are interdependent, so it is an overlapping process rather than a consecutive.

Cycle 1 consists of an ideation phase, a conceptualising phase, a prototyping phase and an evaluating phase. Cycle 2 only consists of an ideation phase. Chapters 5.2 and 5.3 describe each phase for the respective improvements.

5.1.3 Brainstorming with Industrial Design students

Both cycles start with an ideation phase. A well-known method in the Industrial Design field that is often used to gather many, varying ideas is brainstorming (Boeijen & Daalhuizen & Zijlstra, 2020). For both cycles, **brainstorming** is performed with three or four fellow Industrial Design students from different master programs. Figure 56 shows one of the brainstorming sessions. The sessions' results can be seen in Appendix F1 and F2.

5.1.4 Focus Group Brainstorming Session

It is highly valuable to **involve the project's stakeholders and experts** in the design process to gather feedback, share design considerations and iterate on the generated ideas from different perspectives.

The Focus Group
For this project, a Focus Group was set-up, that consisted of:

- one physical therapist (PT) from Rijndam
- one occupational therapist (OT) from Rijndam
- one clinician (C) from Rijndam
- three engineers, one from Rijndam (E1) and two from the TU Delft (E2 and E3)

The session
After the ideation phase of cycle 1, a **Focus Group Brainstorming Session** was set up (Appendix G1, G2 and G3) and performed to discuss and evaluate the ideas that were generated on three identified problems.

The method
For the hybrid session, a modified version of the **SCAMPER** method (only sections A, M and E were addressed) was used and translated to an interactive Whiteboard, as can be seen in Figure 55 (Boeijen & Daalhuizen & Zijlstra, 2020). The experts PT, OT, C and E1 were physically together at Rijndam during the session, so they were able to touch and use the (turned off) device while discussing.

The outcomes
The audio of the session was recorded, the transcription can be found in Appendix G4. During the session, the experts were asked to write their feedback on post-its following the three stages of the **SCAMPER** method. The insights are discussed and considered in the next chapters.

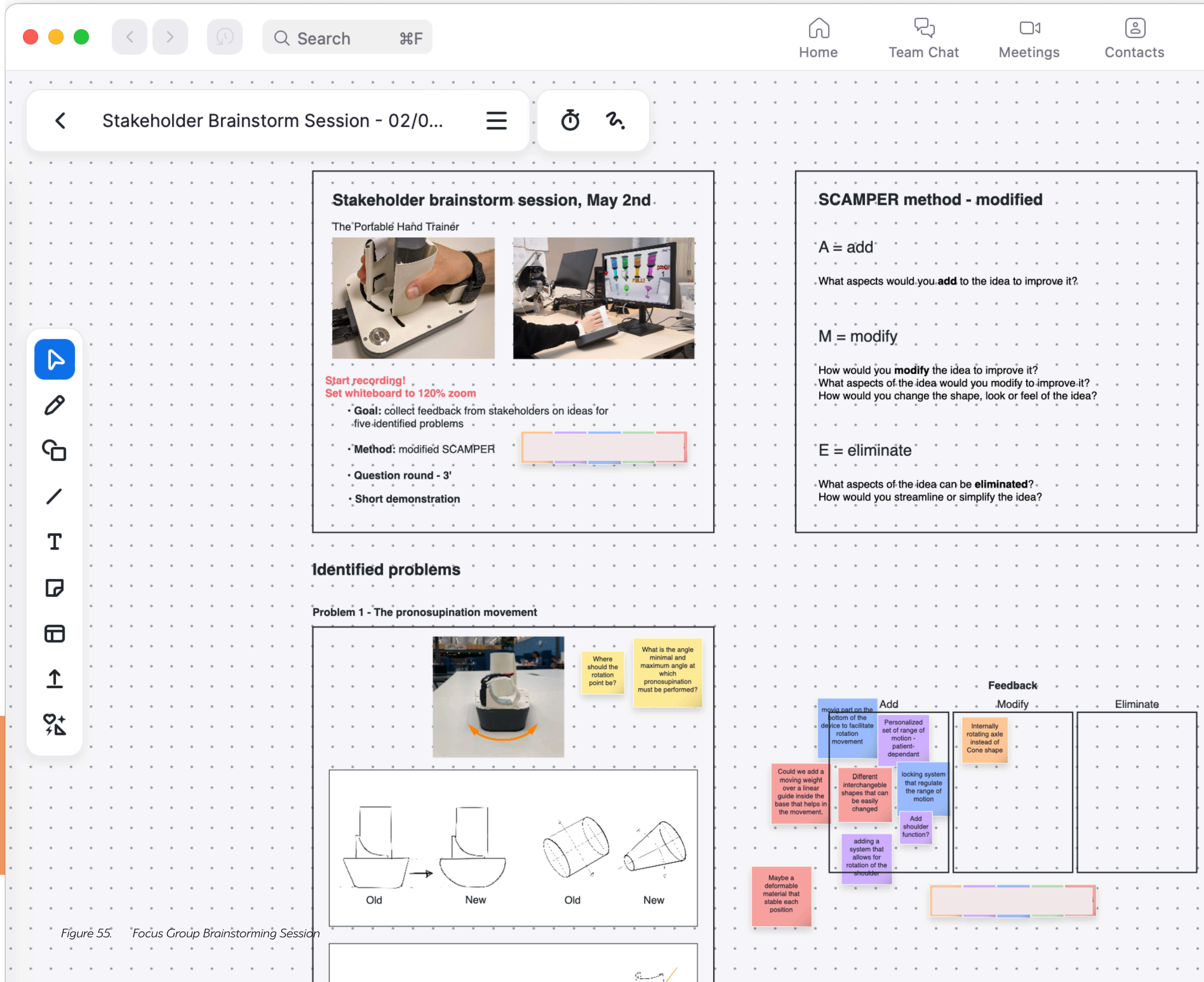


Figure 55. Focus Group Brainstorming Session


Figure 56. Brainstorming session with fellow IDE students

Develop

5.2 Cycle 1

High-priority improvements

5.2.1 Introduction

Cycle 1 is the first of two cycles of the developing phase in which the high-priority improvements are addressed. These are the following:

The device
> Improve unnatural **pronosupination** movements (Chapter 5.2.2)
> Improve the **donning/doffing** of the shell and strap (Chapter 5.2.3)
> Improve the ease of use and ergonomics of the **wrist support and the wrist strap** (Chapter 5.2.4)

5.2.2 Pronosupination movement

Performing the pronosupination movement (Figure 35 and Figure 36) was found to feel unnatural.
The difficulty to tilt the device is primarily caused by the ineffective bottom shape of the device in combination with its relatively high weight. Next to that, the fingertips and the elbow are not in one, straight line while using the device, which also contributes to the unnatural feeling.
The current design can be seen in Figure 48.

Cone-shaped bottom
Experimenting with a different rounding on the bottom of the device was the first step towards a better design. Soon, it could be identified that the device was rolling from left to right rather than in a circular pattern around the elbow. To achieve rolling on circular path, a cone shape on the bottom of the device was introduced instead of a regular cylinder. The transition to a cone shape can be seen in Figure 57 and Figure 63.

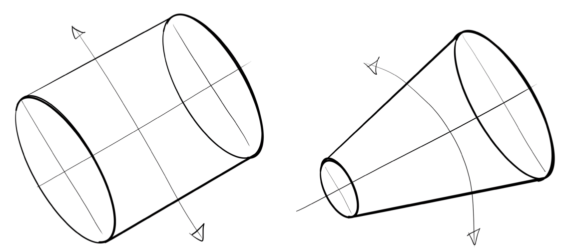


Figure 57. Tube to cone-shaped bottom of device

Two-part bottom
The idea in Figure 57 was **evaluated with the Focus Group in a brainstorming session**. The experts highlighted that it is important to fixate the elbow on a static surface and rotate around the longitudinal axis of the forearm. In a talk with an expert in Biomechatronics and human-machine control, it was identified that an observer (e.g., a physical therapist) cannot see whether a patient is performing the pronosupination movement correctly (as described in chapter 2.2 and seen in Figure 58) (E3, personal communication, 2023).
This insight resulted in a shift from a one-part design to a two-part design. The two-part design has a static, bottom part and a dynamic, top part. In this way, it can be **ensured that the patient is rotating around the longitudinal axis of the forearm** and not performing internal and external rotation around the shoulder.

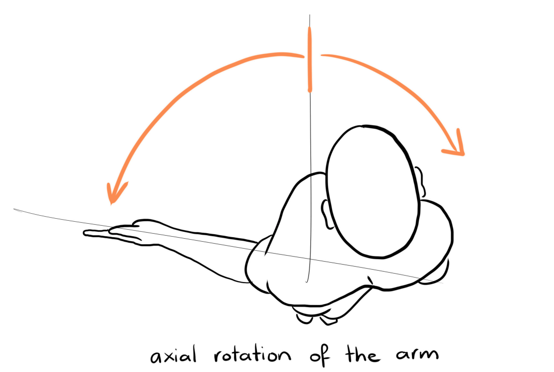


Figure 58. Incorrect movement of arm rotation (adapted from Kapandji, 1982)

Device under an angle
To make sure the elbow and fingertips are in one, straight line while performing pronosupination, anthropometric data from DINED (Huysmans & Molenbroek, 2020) was used to calculate the dimensions of the bottom and top part when the forearm and hand are under **a 12-degree angle**.

Elbow-grip length, Dutch Adults 20-60 y/o, male + female:
P50 = 341 mm

Keeping the height of the current design's body (bright orange in Figure 59) in mind, this resulted in a height of 90 mm at the back of the device and 50 mm at the front of the device.
Different configurations of the static and dynamic parts are compared in Figure 59. Eventually, it was evaluated that the light-pink outlined configuration fits best with the requirements for the product and the scope of the project (Figure 60). This configuration allows to partially duplicate the current design, so it can be ensured that all necessary components fit.

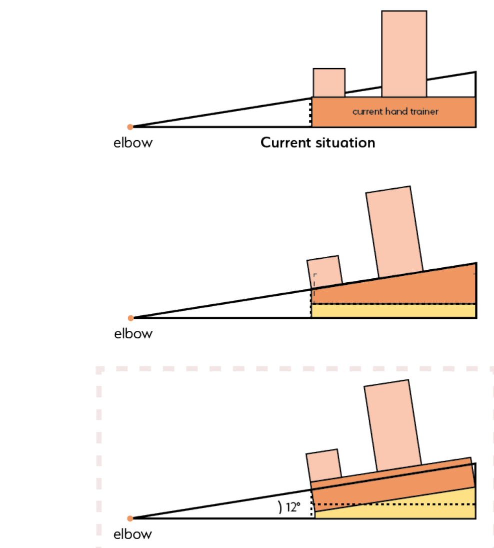


Figure 59. Possible configurations of static and dynamic part of device

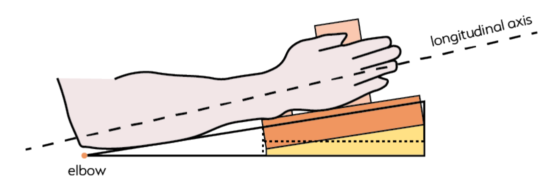


Figure 60. Final configuration of bottom and top part

Rotation around the longitudinal axis
To isolate the pure pronosupination movement and disable other hand and forearm movements, the forearm must rotate around its longitudinal axis. This is achieved when the center point of the circle is placed exactly on the longitudinal axis of the forearm (Figure 60).
Placing the center point exactly at this axis would increase the volume of the whole device to keep enough maximum rotation angle and stability. This consideration was **discussed with three experts** (PT, OT and E2, personal communication, 2023).
It was eventually concluded that the center point should be placed as close to the longitudinal axis as possible but must not negatively affect the device's volume, the maximum pronosupination angle and the device's stability.

Pronosupination angle
The second iteration of the hand trainer enables patients to perform approximately 45-degree pronation and supination. The switch to a two-part design limits the freedom of rotation since it is dependent on the dimensions of the two parts. As explained in the previous paragraph, the negative effect on the body's volume and stability must be considered while experimenting different angles.
After several iterations, the maximum pronation and supination angle is **10 degrees**.

The maximum pronosupination angle can be seen in Figure 61: a section view of the two-part design.

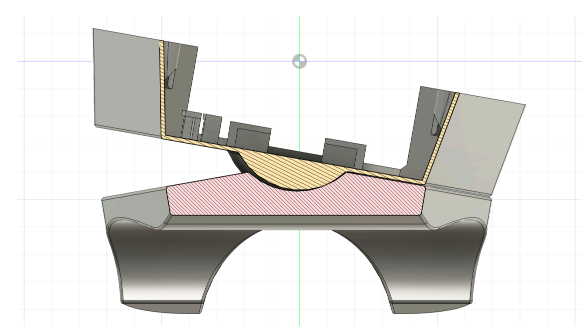


Figure 61. Pronosupination angle (10 degrees) between top and bottom part

Prototyping
Figure 63 and Figure 64 show an overview of the redesign process for the pronosupination movement. The iterations are realised by **low-fidelity prototyping** using **3D printing**. The prints are evaluated by the researcher, fellow Industrial Design master students and experts of the Focus Group. It resulted in a final prototype that is presented in Chapter 6.

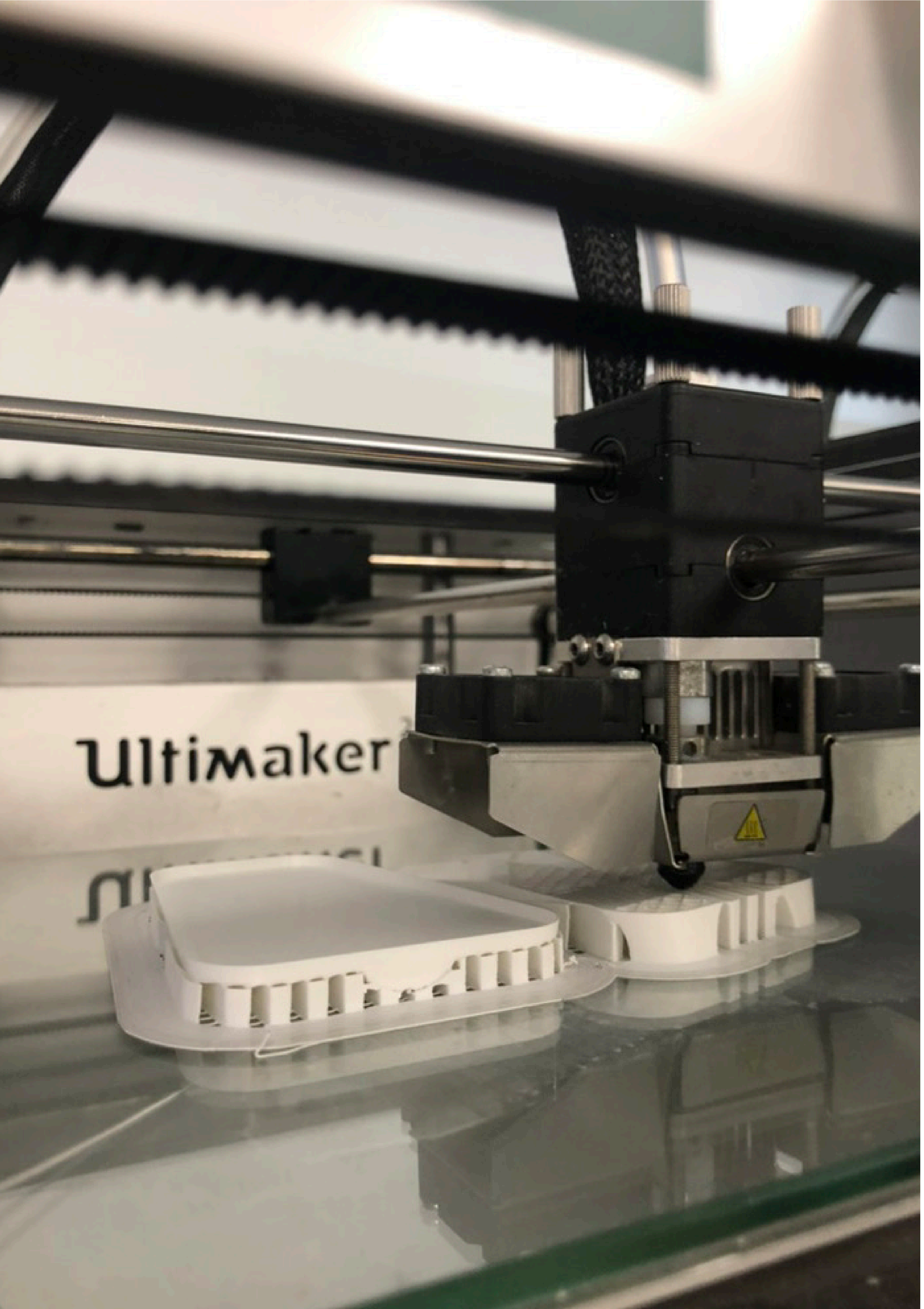


Figure 62. *3D printing scale model base*

Figure 63. *Iterations on different rounding on the bottom of the device, chronologically ordered from left to right*

Figure 64. *Iterations on the two-part bottom design, chronologically ordered from top left to bottom right*

5.2.3 The wrist support

From the usability study, self-testing and peer testing, it was concluded that the wrist support (Figure 65) is lacking in ease of use and is not supporting the ergonomics of the hand and forearm to the utmost. The wrist support does not support both sides of the wrist equally and creates a pressure point on a sensitive spot at the ulna bone. Next to that, the locking mechanism and strap that are currently used are not intuitive and do not support donning from the top (as explained in paragraph 5.2.2).

While assessing the decision matrix in the defining phase (Figure 53), it was assumed that adjustable positioning of the wrist support is necessary and important to add. However, during the **Focus Group Brainstorming Session**, the experts concluded that adjustability is not as important as it was assumed. A simpler and constraining wrist support is favoured over adjustability. Thus, deation was scaled down to improvements on the ease of use and ergonomics of the wrist support.

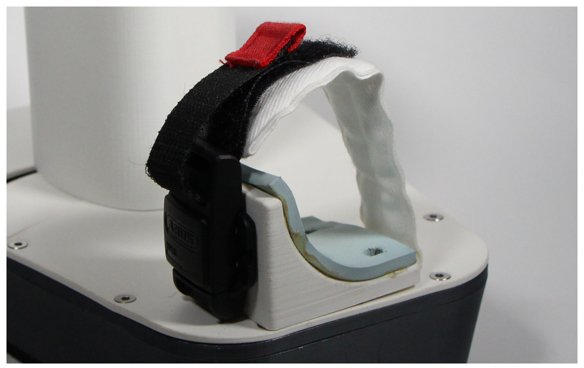


Figure 65. The wrist support

A passive and symmetric system

To align with the idea of facilitating donning from the top, the wrist support could be a passive system in which the wrist can slide into the support, without any further actions required. Thus, ideation was started on different ways to slide into the wrist support from the top. Keeping in mind that the wrist support must support varying wrist sizes, the idea with the most potential is visualised in Figure 66. The bottom part is rigid and symmetric to provide support to the wrist while performing pronosupination. The top part consists of two flexible, symmetric wristbands that bend inwards when placing the hand and form around the wrist after the hand is placed.

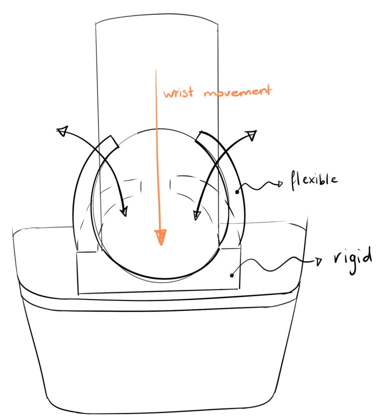


Figure 66. Passive and symmetric wrist support system, front view

A passive and asymmetric system

After a **discussion and test with a physical and occupational therapist**, it was concluded that a symmetric system would not allow patients with spasticity to easily get into the wrist support (PT and OT, personal communication, 2023). Also, the dorsal side of the wrist needs more support than the ventral side because of the outward force while holding the shell. An iteration of the symmetric system can be seen in Figure 67.

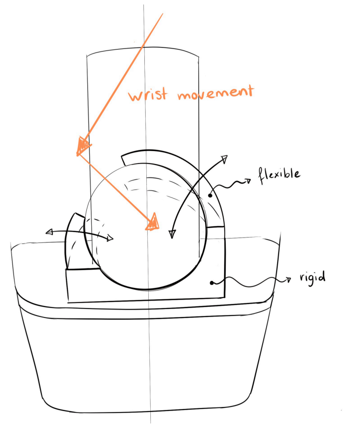


Figure 67. Passive and asymmetric wrist support system, front view

Asymmetric support and symmetric bands

Several iterations of the asymmetric system have been prototyped and evaluated by testing with peers. The iterations can be seen in Figure 71.

After another **discussion and test with a physical and occupational therapist**, it was concluded that an asymmetric wrist support is favoured to provide more support on the dorsal side than the ventral side of the wrist and to support varying wrist sizes (PT and OT, personal communication, 2023). However, asymmetric bands are not as effective as was assumed earlier in the process. The wrist does not necessarily need support on the top (the medial side of the wrist) if the device is not stimulating ulnar and radial deviation.

Therefore, it was decided to use **an asymmetric wrist support and symmetric wrist bands**. The flexible wristbands increase the support on the right and left side of the wrist but also allow it to fit varying wrist sizes (Figure 68).

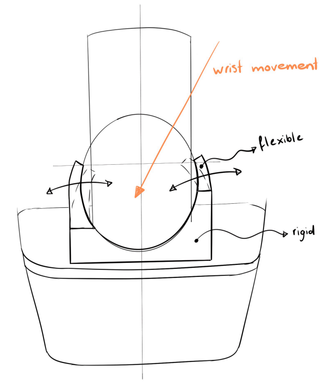


Figure 68. Asymmetric support and symmetric wristbands, front view

The wrist bands material

To achieve the amount of flexibility that is most suitable for its use, several techniques have been used and compared in the ideation and prototyping process. Figure 71 shows the processes of silicon molding, 3D printing in TPU (thermoplastic polyurethane), also experimenting with different infill types and dimensions, 3D printing in Ninjaflex TPU and resin printing Flexible 80A resin.

The results of the four materials have been compared on five aspects (Figure 70). Using a decision matrix, it could be concluded that **Ninaflex TPU** is most suitable for the flexible parts of the wrist support.

The wrist support

It was decided that the wrist support must have an asymmetric shape to provide more support on the dorsal side than the ventral side of the wrist and still allow to fit varying wrist sizes.

Anthropometric data from DINED (Huysmans & Molenbroek, 2020) was used to design the inside shape of the wrist support to reach as much comfort as possible. P75 is taken for exclusively male participants, to make sure relatively large wrist sizes will fit.

Wrist circumference, Decathlon Hand, EU/China, 30-79 y/o, male:
P75 = 185,5 mm

The circumference of the wrist (simplified as an ellipse) can be approximated with the following equation:

$$circumference := 2 \cdot \mathrm{Pi} \cdot \sqrt{\frac{(r1^2 + r2^2)}{2}}$$

By using Maple (Maplesoft, 2022), the radii of the wrist width (r1) and wrist depth (r2) are approximated to:

r1 = 34,5 mm   r2 = 23,5 mm

The complete calculation can be found in Appendix H. Taking additional foam of 3 mm into account, these measurements are translated into the design of the wrist support as seen in Figure 69.

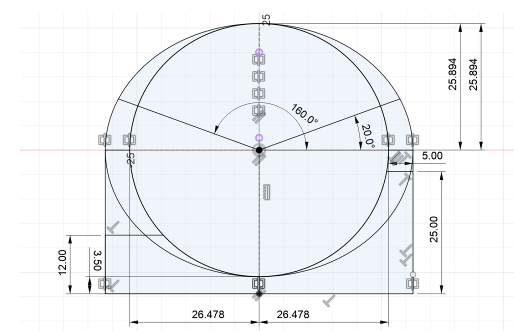


Figure 69. Wrist support dimensions

1t/m5	5 = applicable	5 = suitable flexibility	5 = durable	5 = high comfort	1 = low costs	
factor	**Medical devices applic.***	**Flexibility**	**Durability**	**Comfort**	**Costs****	
weight factor	5	5	4	3	3	**Score**
Flexible 80A resin	2	5	5	5	5	**70**
Elastic 50A resin	5	3	4	5	5	**71**
Ninjaflex TPU 85A	5	4	5	4	2	**86**
Thermoplastic polyurethane (TPU)	5	2	4	2	2	**66**

* *Flexible 80A resin is not MDR certified. Elastic 50A resin, Ninjaflex TPU and TPU are certified materials and already used in healthcare*

** *Flexible 80A and elastic 50A resin cost ± 12,04 euros/product, Ninjaflex TPU costs ± 2,23 euros/product, TPU costs ± 1,82 euros/product*

Figure 70. Comparison of wristbands materials

Figure 71. *Iterations on the bottom support and the wristbands, chronologically ordered from top left to bottom right*

Figure 72. *Silicon pouring*

5.2.4 Donning/doffing

People after stroke that are paralysed on one side of the body still have no or little hand and forearm function when they intend to use the hand trainer during rehabilitation. Subsequently, stroke patients often have spasticity in their hand and wrist which also contributes to the inability to extend their hand around the shell. If people are unable to grasp the shell, the product cannot be used as intended.

Figure 73. Current donning situation from the front

Switching donning steps

After a talk with experts from Rijndam (PT and OT, personal communication, 2023), it was decided to switch around the donning steps prior to product use. First, the patient must place their hand around the shell from the top. Secondly, while moving their hand and forearm down, the wrist must be placed in the wrist support. This donning pattern is visualised in orange in Figure 74.

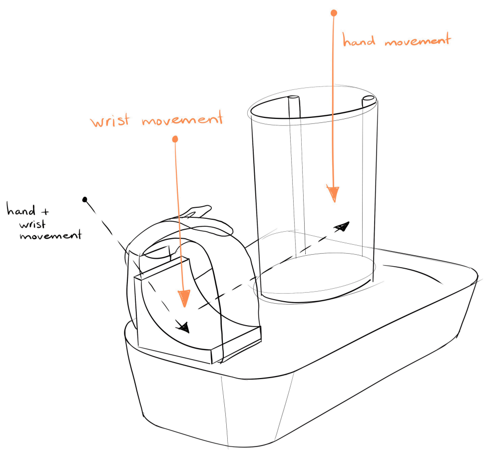


Figure 74. Reshaped donning pattern

A conical shape

To guide the hand around the shell, the idea of using a conical shape on top of the shell arose. Another idea was to guide the hand forward from the back of the shell, however active replacement of the thumb would be necessary. **In a discussion with a phsyical therapist from Rijndam**, this idea was discarded.

Iterations on the cone shape

The shape of the cone has been iterated several times. Based on evaluations and tests with fellow Industrial Design master students, a regular cone shape was transformed into a more funnel shaped design. The first four iterations can be seen in Figure 81.

First test and evaluation

The fourth iteration of the cone, seen in Figure 75, is **evaluated and tested**. The results concluded that the funnel-shaped cone is too wide and does not allow the hand to reach the shell. This situation is imitated in Figure 76.
The iteration that followed is designed to fit on the shell when it is in its closed position, as can be seen in Figure 77.

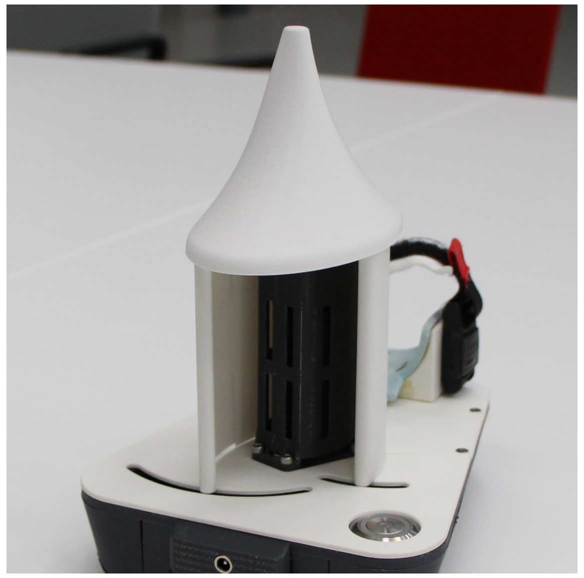


Figure 75. Fourth iteration on donning/doffing cone for evaluation

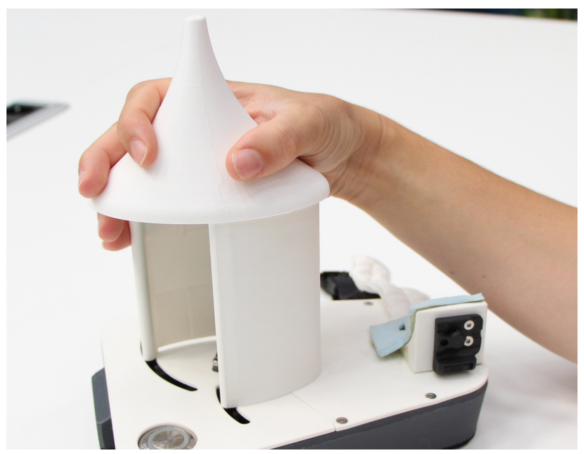


Figure 76. Imitation of person after stroke using the fourth cone prototype

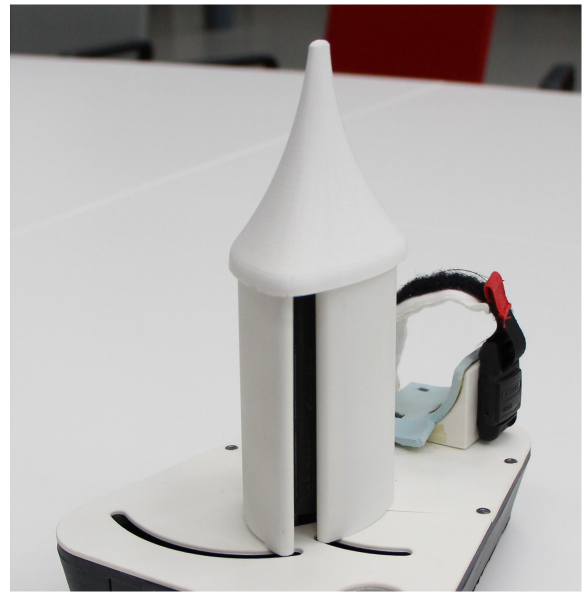


Figure 77. Sixth iteration of donning/doffing cone for evaluation

Second test and evaluation

This iteration is **evaluated and tested** again. The results **are discussed with a physical therapist from Rijndam**, and it was concluded that the width of the cone is adjusted well and people's hands are guided rather smoothly downwards to the shell (PT, personal communication, 2023). However, one flaw was identified which still needed to be considered in another iteration, discussed in the next paragraph.

Helical shape around the cone

The person's wrist is not well aligned with the wrist support when the hand has reached the bottom of the shell. Figure 78 demonstrates this position. Additionally, the thumb irregularly gets stuck at the left bottom corner of the cone (encircled in Figure 78) because the wrist is not fully turned into the right position. By adding a helical shape around the cone, the hand is intended to be guided in the right position to align with the wrist support. Additionally, the bottom of the cone has been rounded more to smoothen the transition from the cone to the shell. The seventh iteration on the cone with the additional helix can be seen in Figure 81.

Figure 78. Imitation of person after stroke using the sixth cone prototype

Third test and evaluation

The helix was intended to smoothly turn the wrist in the right position while moving down to align with the wrist support. However, by **evaluating and testing with experts from Rijndam and an expert in Biomechatronics from the TU Delft** (PT, OT, E3, personal communication, 2023) this addition was discarded. The helix does not guide the wrist as intended. Therefore, the wrist support is adjusted accordingly, which was explained in the chapter 5.2.3.

Attachment to the shell

Since the cone is an addition to the product to enable donning for stroke patients with spasticity, the cone itself must be easy to attach and take off from the shell.
The bottom of the cone (Figure 79) is designed to facilitate this. The front tip of the cone can hook around the right endpoint of the shell. Secondly, the back of the cone can be placed on the small white rectangle that is attached to the battery. This is eased by a chamfer rounding on the bottom surface of the cone.
In a **conversation with an expert from Rijndam** (PT, personal communication, 2023), it was discussed that stroke patients often lack coordination in their hand and forearm which results in rough usage of parts such as the cone. Therefore, the cone slides 10 mm into the thin body of the shell to ensure stability (Figure 80).

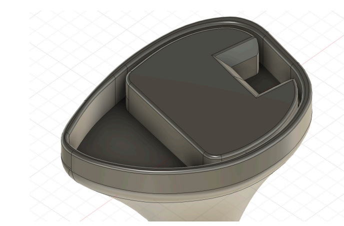


Figure 79. Bottom surface of the cone with cutout

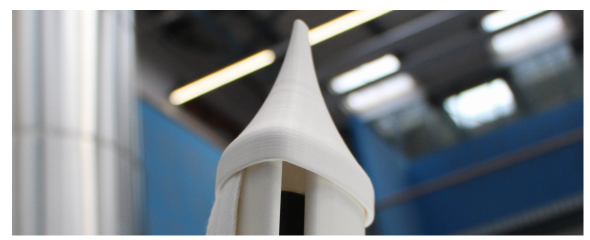


Figure 80. Attachment of cone to shell

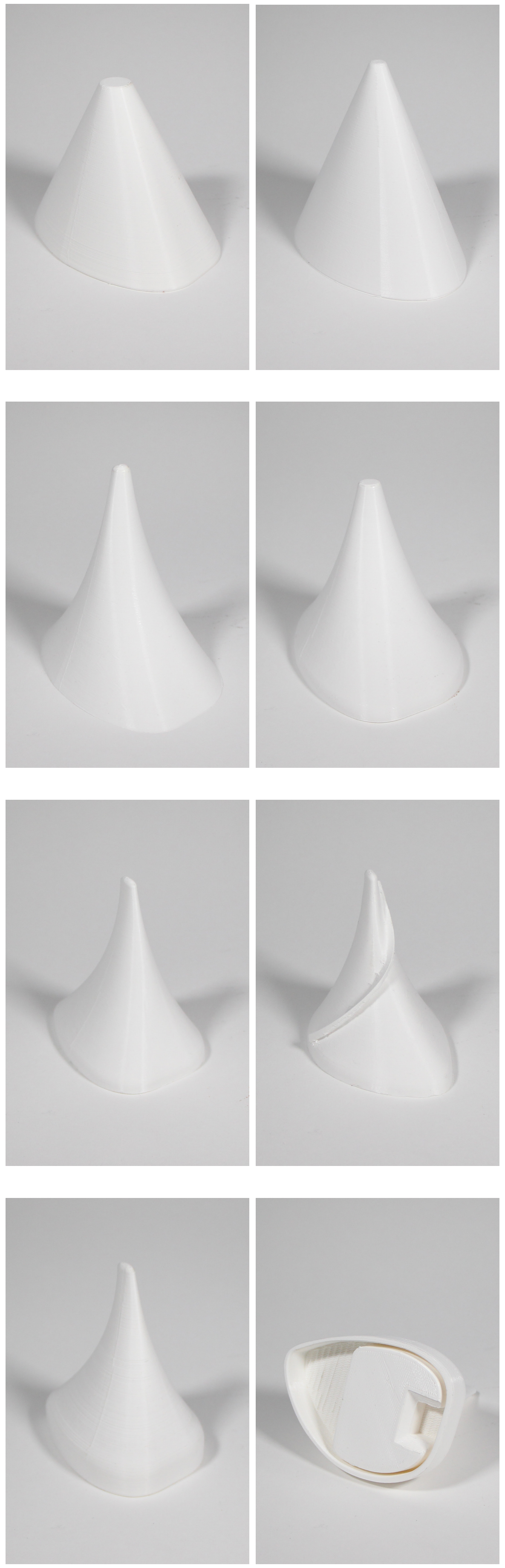


Figure 81. Iterations on the cone, chronologically ordered from top left to bottom right

Key insights

1. The pronosupination movement
The current design does not guarantee a pure pronosupination movement around the longitudinal axis of the forearm.

To achieve this, the device is transformed into a two-part design and titled under a 12-degree angle.

Considering the total volume of the device and the stability of the dynamic part on top of the static part, the pronosupination angle is set to 10 degrees clockwise and anti-clockwise.

2. The wrist support
To support patients in easy donning from the top of the device, the wrist support is transformed into a three-part design: a rigid bottom and two flexible wristbands where the forearm can slide into.

The dorsal side of the wrist needs more support than the ventral side, which led to an asymmetric bottom support design.

The medial side of the wrist does not need support, which led to a partially symmetric wristband design.

3. Donning/doffing
Donning the current device is unfeasible for patients that suffer from spasticity in their hand and forearm.

By introducing an additional organically-shaped cone that can be attached on top of the shell in its closed position, patients are able to don from the top of the device.

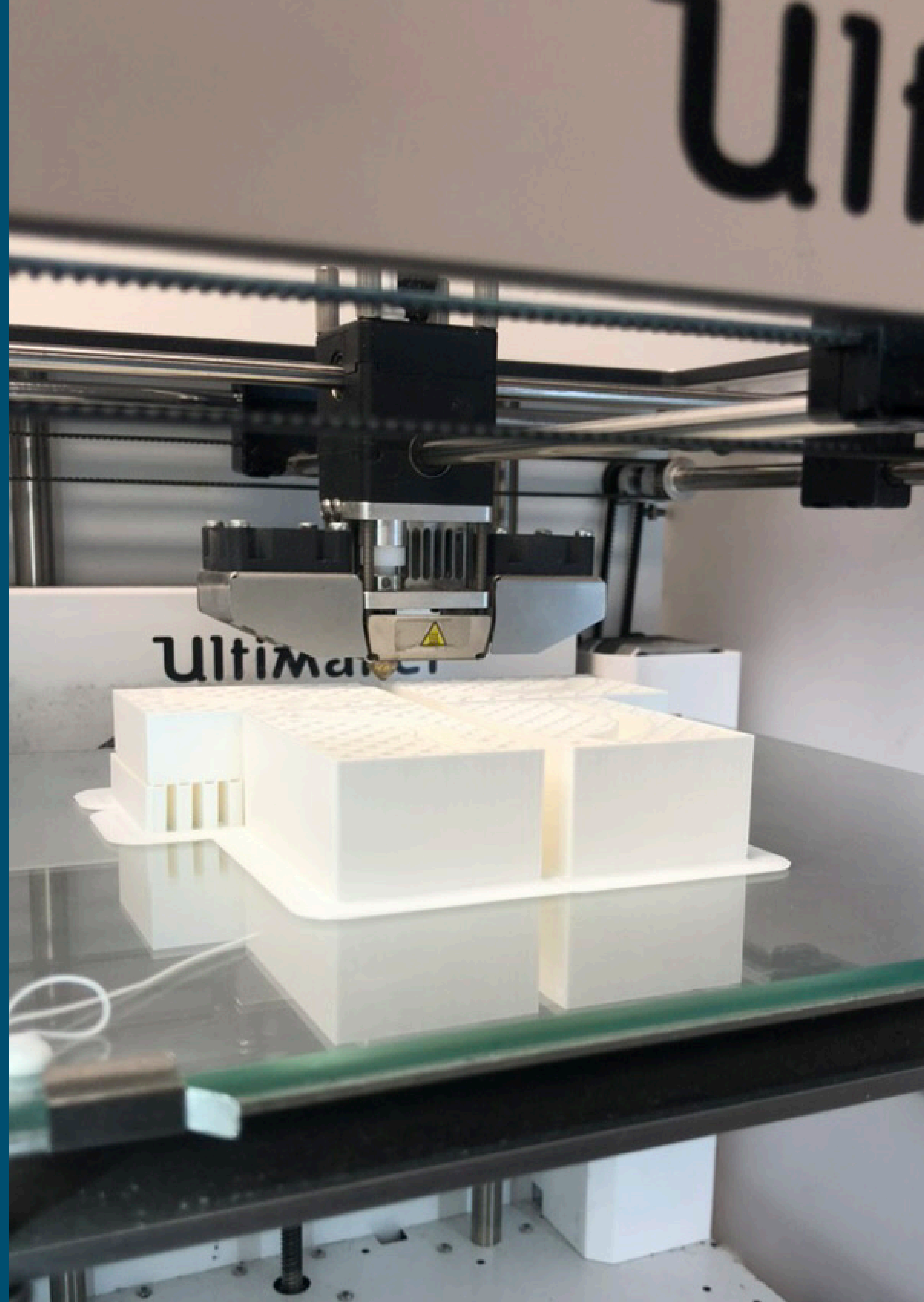


Figure 82 3D printing silicone molding molds

5.3 Cycle 2

Medium-priority improvements

5.3.1 Introduction

Cycle 2 is the second of two cycles in the developing phase, in which the medium-priority improvements are addressed. These improvements are not worked out as far as the high-priority improvements and are not extensively prototyped. Advice on the redesign for these improvements is given in Chapter 6. The medium-priority improvements are:

The device

- Improve the functionality of the **on/off button** (Chapter 5.3.2)
- Redesign the functionality of the **emergency buttons** (Chapter 5.3.3)
- Improve the **finger placement and ergonomics of the shell** (Chapter 5.3.4)

The complete system

- Improve the cleanability (Chapter 5.3.5)
- Improve the sustainability (Chapter 5.3.6)

5.3.2 On/off button

The on/off button that is placed on the top cover of the device (Figure 48) is well located (easily reachable with the unaffected hand), but its appearance is misleading. The button does not only function as on/off switch but is also used to navigate through the introduction pages prior to the game.

The location of the on/off button remains the same because the top cover of the device will not change to avoid a redesign of device's interior structure. The appearance of the button is redesigned. Figure 83 presents different ideas to improve the button design to accommodate its two functions; the result of **a brainstorm session with three Industrial**

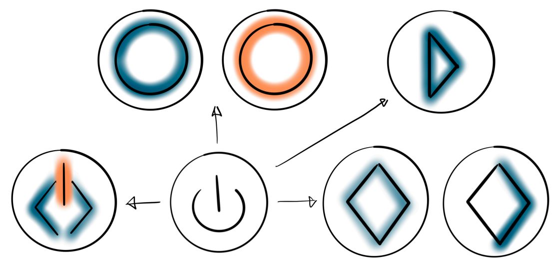


Figure 83. On/off button ideas

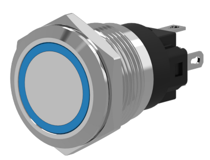


Figure 84. On/off button possibility on the market

Design Engineering students (Figure 92). Ideally, a button is used that visually indicates both its functions, like the design in Figure 83 (bottom right) does. However, due to higher production and development costs, the design on the top left is expected to be favoured. An example of this type of button can be seen in Figure 84, which is already available and ready to use.
Additionally, the light language must change slightly. The light feedback should start directly after the user presses the button, so it is directly clear that it is working and responds to the user's action.

5.3.3 Emergency stop buttons

Currently, the device is equipped with two external emergency stop buttons (Figure 85) that will immediately cut off the power if either of the two is pressed.

Figure 85. Emergency button

One integrated emergency button

Two buttons were necessary because it was designed for an experimental setting. However, in the future use scenario, one button would be sufficient.
Next to reducing to one button, portability would increase if the button were wireless, most likely integrated in the device.
Lastly, the button's appearance is currently overly safe designed, which does not contribute to the feeling of safety when patients use the device.
Several options to improve the emergency stop button(s) are ideated in **the brainstorm session with three Industrial Design Engineering students** and visualised in Figure 86.
Option 2 is expected to be favoured over the other options, because it is easily reachable and rather easy to add to the interior of the device.

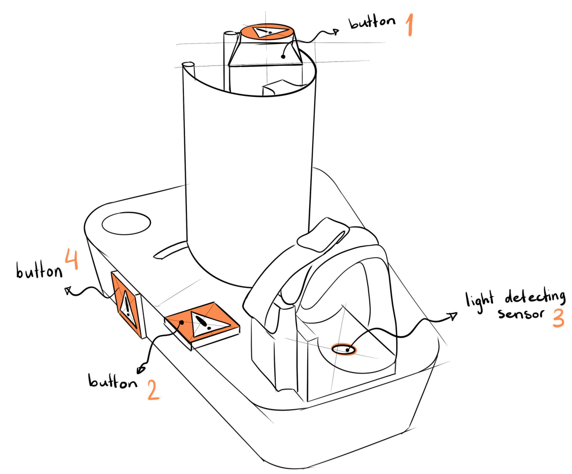


Figure 86. Emergency stop button ideas

5.3.4 The shell

The shell (shown on Figure 48) is one of the main parts allowing the patient to perform flexion and extension movements. The shell sits on the ventral side of the hand and its endpoints are actuated on a circular trajectory while the middle of the shell is fixed. By using anthropometric data, the shell is optimized to follow the motion of a human hand as accurately as possible (see Figure 87) (Kober, 2020).
To include multiple hand sizes, the shell is currently available in three sizes, which are easily replaceable. The shell as it currently is, is cleverly designed to achieve maximum comfort along the whole range of motion. Although comfort has been increased in comparison to the first iteration of the device, finger placement and ergonomics are two aspects that still allow for some improvements.

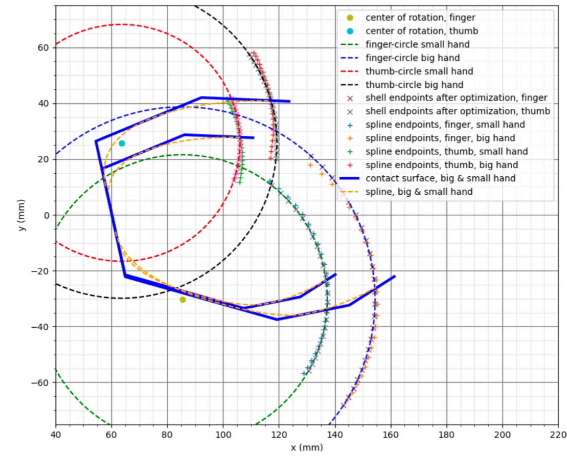


Figure 87. Python optimisation plot to find actuation centers and radii for the different shells (master thesis: Kober, 2020)

The fingers are currently supported by an adjustable strap. However, the thumb and medial side of the hand are not supported. And although the instruction pages show how to place the hand around the shell, the device itself does not have any usecues on hand and finger placement.

Finger placement use cue

To support correct finger placement around the shell during donning, a usecue on the shell could be added to visually explain to the patient how to place the fingers. **The brainstorm session with three Industrial Design Engineering students** resulted in different ways for finger guidance. Figure 88 illustrates several ideas to assist finger placement around the shell.

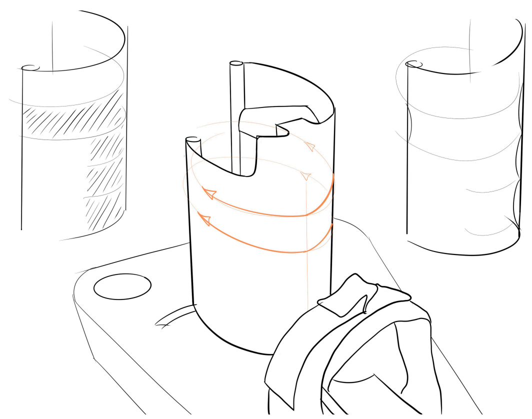


Figure 88. Idea on finger placement around the shell

As visualised in the middle, finger and thumb placement can be assisted by shortening the left side of the shell to indicate that the thumb must be positioned there or by projecting arrows on either side of the shell. As seen on the top left and right, correct finger placement can also be guided

by adding soft dents for each finger or by adding texture on the parts where the thumb and fingers need to be positioned.

Two straps
There is currently one strap positioned on the right side of the shell to support the four fingers while performing extension. Non-hardening clay is used to experiment where support would be desirable around the shell and wrist support. Figure 90 and Figure 91 show the result of this experiment.
Another identified issue was that the **thumb is currently not motivated to perform extension** simultaneously with the four fingers.

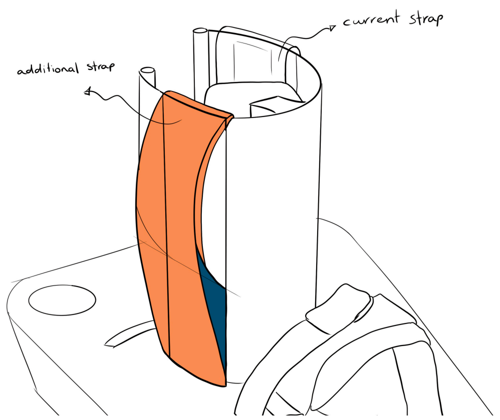


Figure 89. *Second strap on the left side of the shell*

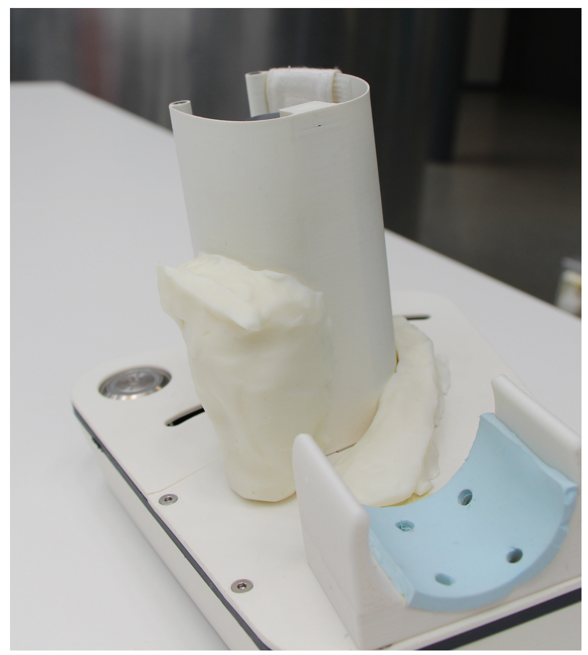


Figure 90. *Experimenting shell ergonomics with clay*

Keeping the limitation of moving and non-changeable parts into account, it is decided to

Figure 91. *Experimenting shell ergonomics with clay*

place a second strap (with extra padding on the lower part) on the side of the thumb to support the thumb during product use and enable the thumb to perform extension. This is visualised in, respectively, orange and dark blue in Figure 89.
Additionally, the strap that is currently used, needs to be loosened and tightened on the inside of the shell, which is not intuitive and not easily reachable. It is advised that the new straps are positioned in a way that they can easily be loosened and tightened on the outer side of the shell.

5.3.5 Cleanability

The hand trainer is a rehabilitation device (in development) which will be used in a medical environment (e.g., inpatient rehabilitation clinic) and most likely be classified as a category I Medical Device (medical devices with low risk) (Business.gov.nl, 2023). Therefore, it is important to take cleanability into account.
Currently, the cleanability rate of the hand trainer is rather good, because the 3D printed parts of PLA are easily cleanable as well as the hypoallergenic padding on the wrist support. However, some possible improvements can be identified:

> the wrist strap and the finger strap are made from fabric, which requires thorough cleaning or replacement once the product switches to another patient.

> the shell mechanism requires two 5 mm slots in the top cover to translate the movement of the shell

Figure 92. *Brainstorm session with IDE students on medium-priority improvements*

rods to the gears in the interior (Figure 28 on page 36). This easily attracts dust and particles and it complicates cleaning by increasing cleaning time since it needs to be done carefully.

> the parting lines between the different outer components and screw spots are not water-resistant which complicates cleaning.

Chapter 6 suggests solutions on improving the cleanability rate for the main parts of the hand trainer: the base, the shell and the wrist support.

5.3.6 Sustainability

There is a growing demand for products that minimise environmental impact throughout their lifecycle, optimise resource use and contribute to the well-being of individuals and nature. In product development, sustainability must be considered throughout the whole design process, from the exploring phase until the product is ready to be introduced to the market. Sustainability can be considered in many different aspects of product design, such as material selection, production process, durability and waste reduction.

The second iteration of the hand trainer does already consider its environmental impact. However, improvements can be made.

> Keeping in mind that the hand trainer is a medical product and needs to meet specific regulations, PLA is a sufficient material selection. It is more environmentally friendly in comparison to traditional plastics (Ansys, 2023).
However, the process of 3D printing may be good to replace by another production process to increase sustainability.

> The different parts of the product are easy to disassemble to minimize waste. In this way, the PLA parts and the electronic components are rather easy to reuse.

> The product is not designed to fit all patients but does include varying hand and forearm sizes to minimise the need for personal adjustments. The adjustable shell is for example easy to replace. Ideally, a 'shell-that-fits-all' is used to increase the sustainability rate.

Chapter 6 provides suggestions on improving the sustainability rate for the main parts of the hand trainer: the base, the shell and the wrist support

Key insights

1. The on/off button
The location of the on/off button is easily reachable, but the appearance is misleading. The redesign that covers its two functionalities removes confusion.

2. The emergency stop buttons
The two emergency stop buttons are reduced to only one button that is integrated in the physical device.
The appearance of the buttons is bulky and exaggerated. The redesign is envisioned to be subtle but still functional.

3. Finger placement and ergonomics of the shell
The thumb is currently not supported and the medial side of the fingers is not supported enough. To achieve sufficient effective support, an additional strap with thicker cushioning on the bottom is added to the left side of the shell. And to support finger and thumb placement, the left side of the shell is shortened and a usecue is added on the outer surface of the shell.

4. Cleanability
Cleanability can be improved by redesigning the top cover into a water- and dusttight design by removing or enclosing slots, screws and parting lines.

5. Sustainability
Sustainability can be increased by further optimising the device for easy disassembling and avoiding personalised parts.

5.4 Towards the final prototype

5.4.1 Introduction
This chapter presents a plan to combine the promising ideas on the high-priority improvements from the diverging phase and turn that into a feasible, viable and functional hardware-ready 3D (high-fi) prototype to present at the World Haptics Conference at the TU Delft.

5.4.2 Goal
The goal of this graduation project is to have a 3D final prototype that is hardware-ready for usability testing later in the year. An interim goal for this project is to present the redesign of the hand trainer at the World Haptics Conference of the TU Delft on July 11th. The hardware-ready prototype from this graduation project is then connected to the redesigned GUI and functionality of the game.

5.4.3 Approach
The three high-priority improvements need to be integrated into the final prototype of the redesigned hand trainer. The improvements must be working well in the assembly but do not need to be 100% perfect, since it is still the beginning of an ongoing development process. Recommendations for future work are discussed in Chapter 9.

Reusing old components
To avoid redesigning the interior structure of the hand trainer, the improvements on the hand trainer are based on the current shape of the top covers. In this way, the top covers, the shell and electronic and mechanical components can be reused without reorganisation of the interior components. Figure 93 shows the old prototype: the white parts and above, except for the wrist support, can be reused. The anthracite bottom needs to be replaced.

Figure 93. Old prototype of the hand trainer

Steps to take
The following steps need to be taken to reach a final prototype that is hardware-ready and connected to the game:

1. 3D print the necessary components in GreenTec white, GreenTec anthracite and Ninjaflex TPU.
2. Assemble the wrist support and add 3 mm padding for comfort
3. Add inserts to the newly printed bottom part
4. Disassemble the old hand trainer prototype
5. Transfer the top covers, the shell and all electronic and mechanical components from the previous hand trainer to the newly 3D printed parts
6. Assemble all components and screw down
7. Test the new prototype on hardware, software and the system together

Figure 94. Preparing 3D printed molds for silicon pouring

6 Final prototype

Chapter 6 presents the result of this master thesis, an improved design of the portable hand trainer. The first paragraphs introduce the complete product system and present the hardware-ready 3D final prototype by highlighting three improvements on the physical device that were discussed to have the highest priority. The last paragraphs give advice on the graphical user interface and the game design that accompany the physical device.

This chapter is structured in the following parts:

6.1 The portable hand trainer

The third iteration of the hand trainer in the complete system

6.1.1 Introduction

This chapter introduces the result of this master's graduation project, a redesign of the portable hand trainer.

6.1.2 The physical device, the GUI, the game and the complete system

By researching and identifying the flaws and opportunities of the current system, a list of possible improvements was created and prioritised, distinguishing the physical device, the GUI, the game and the complete system. The next subchapters present the **redesigns for the high-priority improvements** (Chapter 6.2-6.4) and **advice on the medium-priority improvements, the GUI and game design** (Chapter 6.5-6.7).

The third iteration of the hand trainer

The final prototype of this project is a redesign of the second iteration prototype on three high-priority improvements: **1. the pronosupination movement, 2. the wrist support** and **3. donning and doffing** (Figure 95). The advice on the medium-priority improvements, GUI and game design are not integrated in the final prototype. The parts of the product that are adjusted in comparison to the previous iteration of the hand trainer are: 1, the base, 2. the wrist support and 3. the shell. These product parts are discussed in the next subchapters.
The detailed dimensions of the hand trainer can be seen in Appendix I1.

The physical device in the complete system

Figure 95 illustrates the third iteration of the hand trainer within the complete system, including the GUI and the game. Although the steps prior to product use and product-to-software communication changed by introducing this redesign, the purpose of the device and the goal of the game did not change throughout this project.

Figure 95. Third iteration of the portable hand trainer

6.2 The base

6.2.1 Introduction

This chapter proposes a **redesign** for the base of the hand trainer. The base is a crucial part of the product that accommodates the **pronosupination movement** of the forearm, an important rehabilitation movement for upper limb rehabilitation, as explained in Chapter 2.2.

6.2.2 Reasoning for redesign

In the second iteration of the hand trainer, the base of the product was accommodating a pronosupination **movement that felt unnatural**. It was also identified that the device **does not gaurantee practice of the pronosupination movement in the right way**, as explained in chapter 5.2.2.

6.2.3 The final design

The redesign of the base consists of two parts, the **static** (bottom) and the **dynamic** (top) part (Figure 96). The dynamic part moves on top of the static part, following a circular trajectory. Figure 100 and Figure 101 illustrate this movement.

The base of the device is designed to fit perfectly on the top cover of the previous (second) iteration of the hand trainer (Figure 97) to avoid the necessity of restructuring the internal components of the device.

A 12-degree angled base

To isolate the pronosupination movement as pure as possible, the device is tilted under an angle. This **12-degree angle** makes sure that the middle of **the hand and the elbow are in one, straight line** while using the product, as can be seen in Figure 98.

Figure 96. The base: the dynamic and static part

Figure 97. Top cover of the hand trainer

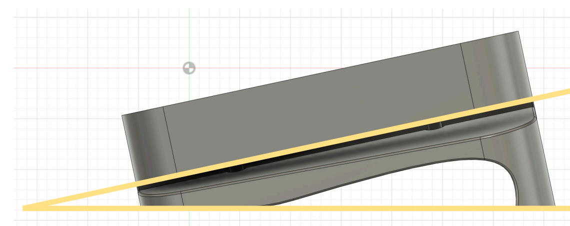


Figure 98. 12-degree angle between the device and the table

A 10-degree pronosupination angle
The patient can perform pronosupination by rotating the dynamic part on the static part while opening the shell by extending the hand. The dynamic part can rotate **10 degrees**, both clockwise and anti-clockwise. This rotation can be seen in Figure 100 and Figure 101.

In the ideal situation, the center point of the circle that the dynamic part is rotating around (seen in Figure 99), lies exactly on the longitudinal axis of the forearm. In this final prototype, the center point of the circle lies approximately 70 mm lower to avoid a decrease in stability and an increase in product volume. Moreover, this also decreases the force that needs to be exerted by the patient to rotate the device.
The general product dimensions of the base can be seen in Figure 102.

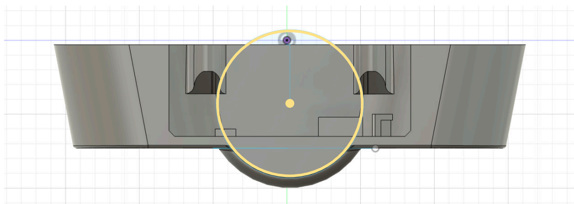


Figure 99. Centerpoint of rotation circle

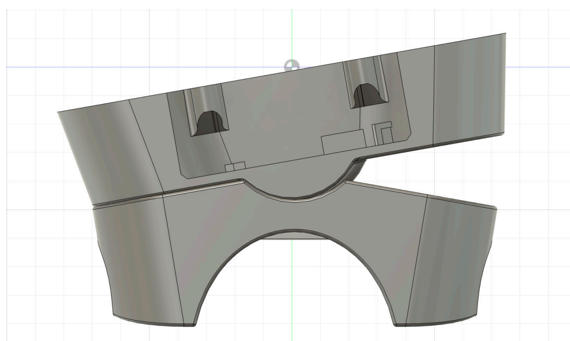


Figure 100. 10 degree rotation clockwise

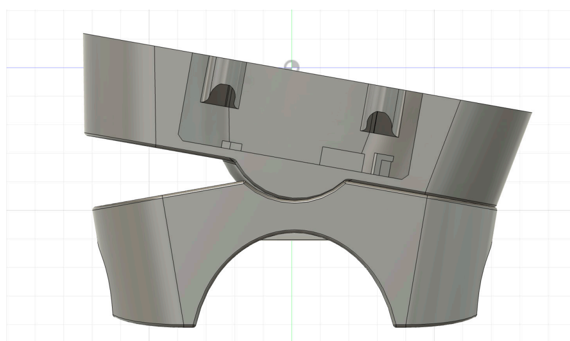


Figure 101. 10 degree rotation anti-clockwise

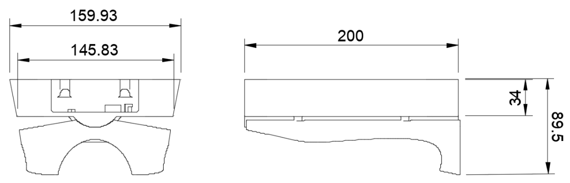


Figure 102. Product dimensions of the base (in mm)

6.2.4 The static part
The **static part** (Figure 103) is the part that will be standing on an external, flat surface during product use and has a circular cut-out in which the dynamic part can rotate. The bottom is covered with anti-slip material, so it does not easily slide away and does not stimulate external and internal shoulder rotation.

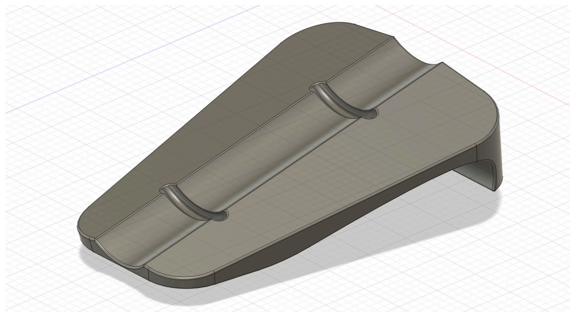


Figure 103. The static part of the base

The static part is symmetric along the vertical axis and the shape (from top view) is based on the bottom surface of the dynamic part.
Material use is decreased by creating an organic and hollow shape.

The detailed dimensions of the static part can be seen in Appendix I3.

6.2.5 The dynamic part
The **dynamic part** (Figure 104) is used on top of the static part and rotates around the cylinder extension on the bottom surface (Figure 105). The cylinder has two additional smaller circular tubes that fit exactly in the two circular cutouts of the static part to ensure stable movement.

The dynamic part is hollow to fit the electronic and mechanical components with an outer wall of only 1.5 mm. The part is tapered from the top to the bottom to create a less bulky-looking device and it has a slot on the back where the cables block fits. The interior has four small extensions to enclose

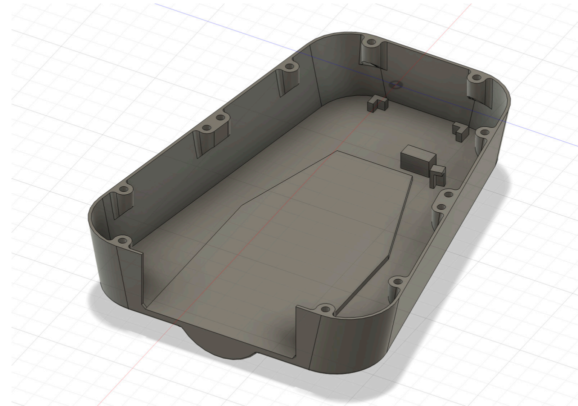


Figure 104. The dynamic part of the base

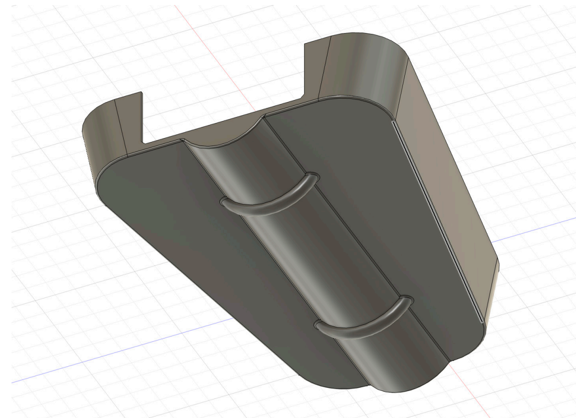


Figure 105. The dynamic part of the base, bottom

two PCBs and one larger extension that connects with the top cover of the device.

The detailed dimensions of the dynamic part can be seen in Appendix I2.

6.2.6 Materials
The static and the dynamic part of the base are 3D printed in GreenTec black, a material that is FDA approved for foodsafe. The bottom of the static part is covered with black anti-slip foam. Since the bottom of the device is not constantly in contact with the skin, it does not need to be medically certified.
To attach the top cover to the dynamic part, M3 inserts and M3 screws are used.

6.2.7 Sustainability
Material use is decreased by making the dynamic part and static part hollow and by optimising the volume of the static part.

Currently the dynamic and the static base are 3D printed. It is advised to do research on other production processes that would positively affect the sustainability rate of the device.
The static part does not have any other material, so the recycling process is rather simple. The recycling process of the dynamic part is simplified by using screws instead of glue.

The product will approximately be used for a relatively short period of time, approximately three months. However, after an extensive redesign on cleanability, the product can easily be disinfected after each patient and transferred to another person. The durability of the product will drastically increase, and so will the sustainability rate.

6.2.8 Cleanability
The static part has a smooth surface and is therefore easy to clean. It does not have any holes, parting lines or slots so materials cannot get in. Once the production process of 3D printing is replaced by another suitable production process, e.g., injection molding or vacuum forming, an IP69 rate can be reached.
The transversely located tubular cutouts in the middle with a diameter of 6 mm need attention during cleaning since dust and other materials can rather easily locate there and stay. However, the cutout is most of the time covered by the dynamic part, which minimises the chance to attract dirt.

The dynamic part is hollow but covered by the top covers. The parting lines are on the side of the product which means they are less likely to get dirty and attract dust. It is eventually advised to make sure the parting lines are removed or covered by additional material, so the dynamic part can easily be disinfected and the electronic and mechanical components are protected.
Ideally, the use of screws to attach this part to the top cover is replaced by an attachment mechanism that, for example, uses clicks in the interior of the part that enables the top cover to be one smooth surface.

6.3 The wrist support

6.3.1 Introduction
This chapter proposes a **redesign** for the wrist support of the hand trainer. The wrist support is a crucial part of the product that supports correct performance of the **pronosupination movement** of the forearm, an important movement for upper limb rehabilitation.

6.3.2 Reasoning for redesign
In the second iteration of the hand trainer, the wrist support was **lacking in ease of use** and **did not support the ergonomics of the hand and forearm** the utmost. The previous wrist support would not support donning from the top well.

6.3.3 The final design
Figure 107 shows the final design of the wrist support. The wrist support consists of the **bottom support** and the **wristbands**. Note that the wrist support is designed for right-hand usage, to comply with the design scope of this project.

The bottom support is rigid and primarily supports the wrist on the dorsal side to withstand the exerting force of the wrist outwards.
The wristbands are flexible and give additional, less tough, support to the dorsal and ventral side of the wrist.
The general product dimensions of the wrist support can be seen in Figure 106. The detailed dimensions can be found in Appendix I4.

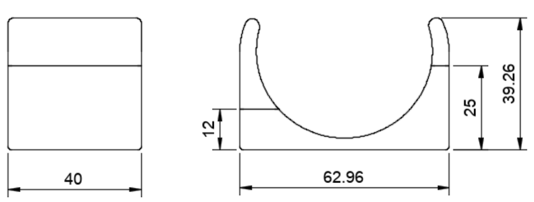


Figure 106. Product dimensions of the wrist support (in mm)

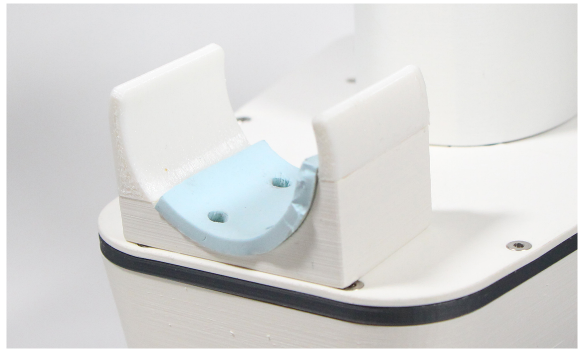


Figure 107. The wrist support

6.3.4 The bottom support
The bottom support (Figure 108) serves as support to the lateral, dorsal and ventral side of the wrist and is attached to the top cover of the device by four screws.

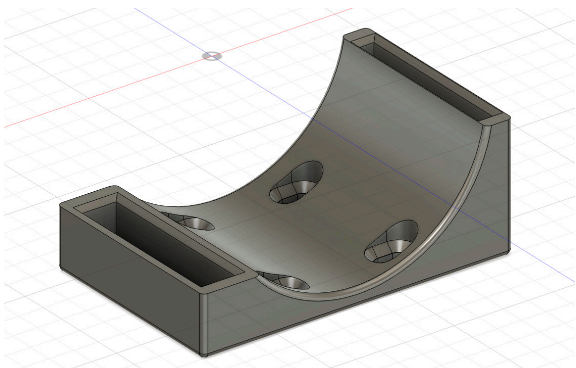


Figure 108. Bottom support

It is covered with hypoallergenic padding material to increase comfort on the lateral side of the wrist where the ulna is visible. It supports 40 mm on the lateral side, 12 mm on the ventral side and 25 mm on the dorsal side of the wrist.
It has a slot on both sides where the wristbands can neatly slide in to attach to the wrist support, as can be seen in 50% opacity model in Figure 109.

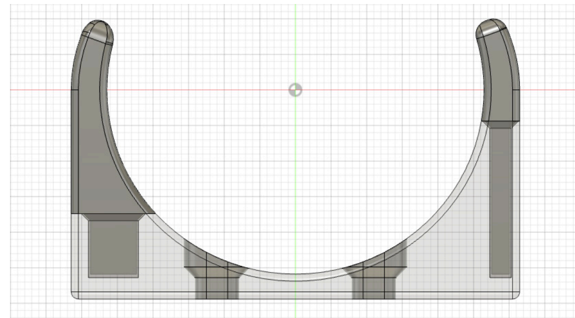


Figure 109. Attachment system between bottom support and wristbands

6.3.5 The wristbands
The wristbands (Figure 110) serve primarily as support for the ventral and dorsal side of the wrist but also support the medial side of the wrist slightly for patients with thinner wrist sizes. The bands are

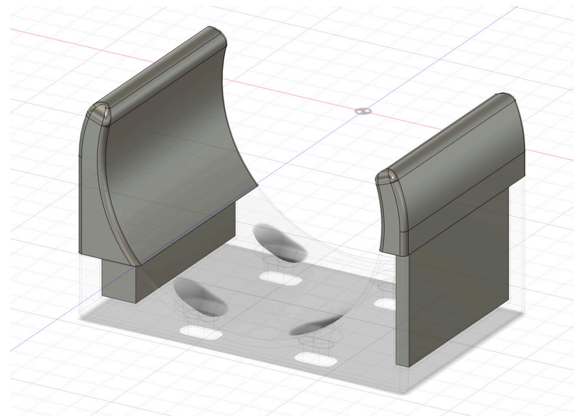


Figure 110. Wristbands

flexible so they can change its shape to varying wrist sizes and can follow the forearm movement when patients have trouble sliding into the wrist support.
The endpoints of the wristbands are approximately 4.5 mm and are symmetrically shaped according to human wrist dimensions (Figure 111) (DINED, 2023).

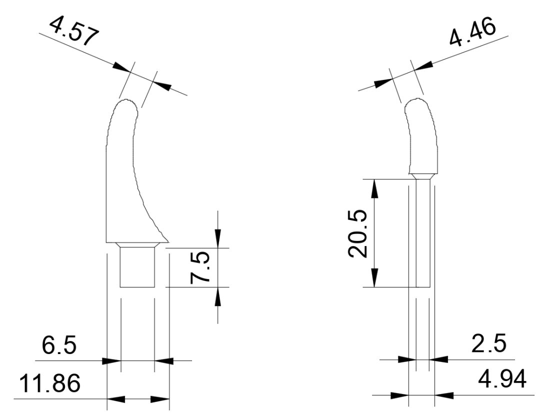


Figure 111. Product dimensions wristbands (in mm)

6.3.6 Materials
The bottom support for the final prototype is currently made of GreenTec white, a FDA approved material for foodsafe. Hypoallergenic thermoplastic padding material Nora Astro Form 8 (Van Drunen, n.d.) is used to cover the surface of the bottom support. The wristbands are made of Ninjaflex TPU, a medically approved, flexible 3D printing material (NinjaTek, 2021). The bottom support is attached to the top cover with four M3 screws.

6.3.7 Sustainability
The wrist support is designed to support varying wrist sizes, so no personalised parts are necessary. This increases the durability of the wrist support. The foam is easily cleanable, so it does not need to be replaced when transferring from one patient to another. However, the foam is currently glued to the bottom support which makes it harder to disassemble and recycle. A clever attachment system that avoids glue would increase the recyclability of the foam and the bottom support.
The wristbands are less durable than the bottom support since they most likely tear after a shorter period of use. This could be tackled by optimising the bands to minimise the possibility to tear.
The wristbands are currently glued into the slots of the bottom support. A clever attachment system where glue is not necessary would increase the recyclability of wristbands and the bottom support.

Currently both parts are 3D printed. Another production process may be good to use that will positively affect the sustainability rate of the whole device.

6.3.8 Cleanability
The bottom support has a smooth surface which makes it easy to clean. Although the screws and screw holes allow for dust and dirt to get in, by removing the screws, it is easily cleanable. The wristbands have an enclosed smooth surface (IP69), which makes it easy to clean and no difficulties are foreseen.

6.4 The shell

6.4.1 Introduction
This chapter proposes a **redesign** for the shell of the hand trainer. The shell is a crucial part of the product because its main function is to accommodate the **flexion and extension movement** of the hand, an important rehabilitation movement for upper limb rehabilitation. The shell also supports the **pronosupination movement** of the forearm.

6.4.2 Reasoning for redesign
The shell of the hand trainer was already cleverly designed to achieve maximum comfort along the whole range of motion.
The second iteration of the hand trainer however did not consider that **donning from the front is almost unfeasible** for people after a stroke, since spasticity makes it difficult to extend the hand around the shell.
Additionally, **finger placement around the shell** and **ergonomics** are two aspects that also allowed for some improvements.

6.4.3 The final design
The final design is presented in the next two paragraphs, distinguishing a redesign for the shell itself and the cone, an addition on top of the shell.

6.4.4 The shell
In the previous iteration of the hand trainer, the shell was already cleverly designed to achieve maximum comfort along the whole range of motion during flexion and extension (Figure 87).
In this redesign, an additional strap on the left side of the shell is added to support the thumb during flexion and extension (Figure 112). The extra strap also nudges the people how they need to place their thumb and fingers around the shell.

A usecue is added to the outer surface of the shell to contribute to creating better guidance on the finger placement around the shell. This is visualised in Figure 112.

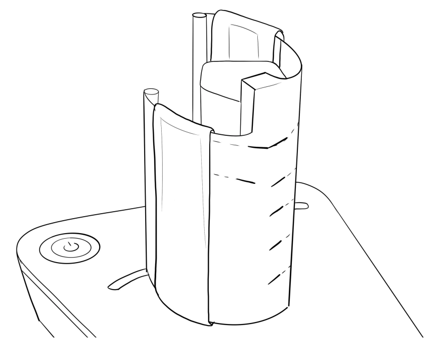


Figure 112. Additional strap and usecue on the outer surface of the shell

6.4.5 The cone
The cone (Figure 114) is an additional part to the parts that already existed in the device.
It is designed to support donning from the top of the device instead of the front for people who cope with spasticity and cannot open their hand by themselves yet.
The cone is inspired by a conical shape, which allows it to smoothly guide the patient's hand around the shell.
The general dimensions of the cone can be seen in

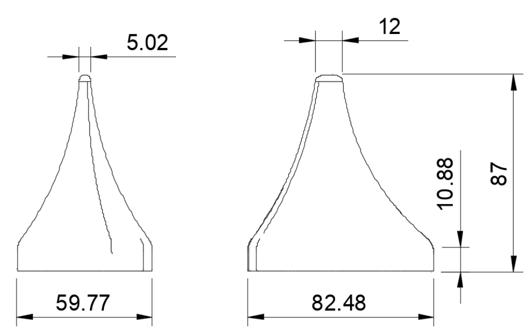


Figure 113. Product dimensions of the cone (in mm)

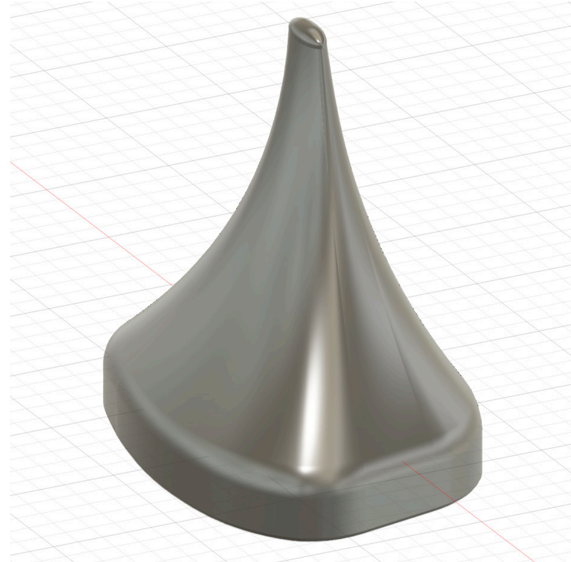


Figure 114. The cone

Figure 113. The detailed dimensions can be found in Appendix I5.

Attaching the cone to the shell
The cone has a slit of approximately 1.5 mm on the bottom surface which allows it to be placed 10 mm over the top of the thin shell in its closed position (Figure 115). Together with the rectangular cutout, these are two reference points for the user to place the cone on the shell.

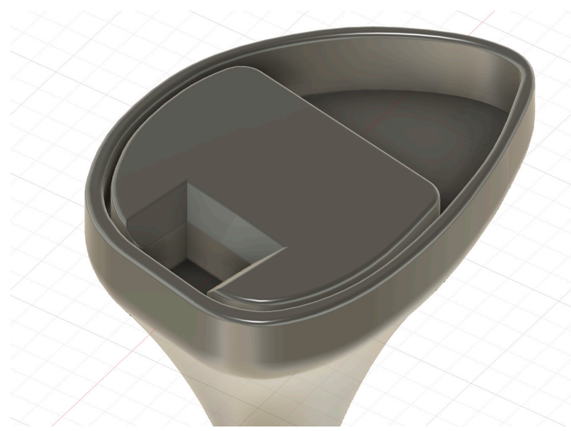


Figure 115. Bottom surface of cone, attachment to the shell

To make sure the attachment of the cone to the shell is as easy as possible for stroke patients, the rectangular cutout is accompanied with a chamfer fillet so the cone can slide into the shell. Figure 116 shows how the cone is placed on the shell as efficiently as possible.
Figure 117 shows the general dimensions of the bottom surface.

Figure 116. Use scenario of attaching the cone to the shell

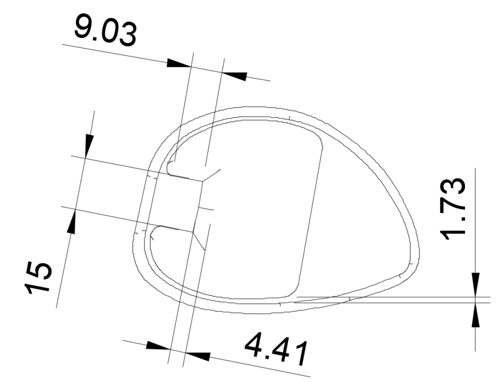


Figure 117. Bottom surface of cone dimensions (in mm)

6.4.6 Sustainability
The shell comes in three different sizes to support varying hand types of patients. This means that the cone also needs to have the ability to be placed on three shells with varying dimensions. It is advised to redesign the cone in such a way that it fits and works for all shells, so it becomes one universal part. Otherwise, three different cone sizes would have a negative impact on the sustainability rate.
Although it is an additional part of the device and increases material use accordingly, the cone is solid and not easy to break. This durable design has a positive effect on its sustainability rate.
Lastly, the cone is attached to the shell without any additional materials, so it can easily be disassembled and recycled.

6.4.7 Cleanability
The outer surface of the cone is smooth so this part can be easily cleaned. The cutout on the bottom surface is rather difficult to clean but is often covered by the shell. In a redesign, the slit could be wider and would therefore be easier to clean.

6.5 Accessories

The main button and the emergency buttons

6.5.1 Introduction

This chapter proposes **advice** on redesigns for the two accessoiries of the hand trainer: the **on/off button** and the **emergency buttons**.

6.5.2 The main button

The main button (previously called 'the on/off button') has two functions: turning the device on and off, and navigating through the instruction pages in the game prior to product use (Figure 118). This paragraph proposes an advice for redesigning the main button.

Figure 118. The current on/off button of the device

The main button's location is advised to remain the same, since it is easily reachable with the unaffected hand and is aesthetically pleasing.

It is advised to remove the light circle around the on/off logo and replace the on/off logo by the design that is illustrated in Figure 119.
This design combines the button's two functions in one logo. If the device is turning on or off, the whole logo will light up. If the patient is navigating through the game, only the two arrows will light up.

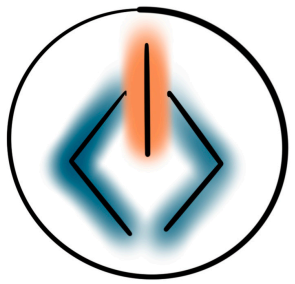


Figure 119. Logo design

6.5.3 The emergency stop buttons

Currently, there are two emergency buttons (Figure 120). First of all, it is advised to reduce it to one emergency button and transform it to an integrated button in the physical device. The button must be easily reachable with the unaffected hand to ensure safety.

Figure 120. The current emergency buttons of the device

It is advised to place the single emergency button on the left side of the dynamic part, to ensure the patient can easily reach it with their unaffected hand while using the device. Figure 121 shows this location. By placing it on the dynamic part, it can easily be integrated to the already existing

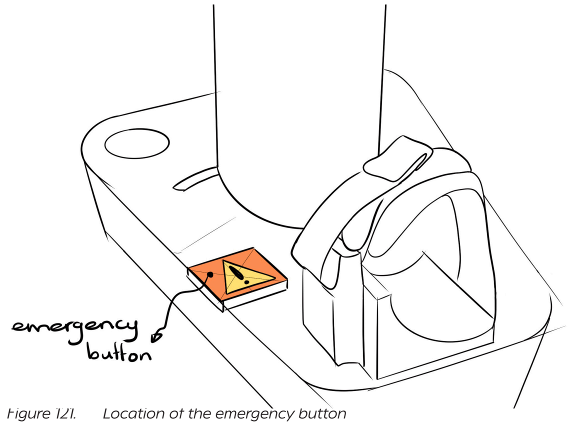


Figure 121. Location of the emergency button

electronic circuit in the interior of the device.
Figure 122 shows a redesign of the appearance of the emergency button. By placing a exclamation mark on the top, it is indicated that the button can be pressed in case of emergency. However, this also needs to be informed by the therapist in an introductory talk. The exclamation mark could also be replaced by the word 'STOP'. The color orange is currently chosen and can be accompanied by yellow details.

Figure 122. Design of the emergency button

6.6 Graphical User Interface

6.6.1 Introduction

This chapter gives **advice** on the **graphical user interface (GUI)** of the instruction pages prior to the game that is used in combination with the hand trainer. The advice is based on the decision matrix that was formed in the defining phase of the project.

6.6.2 Advice on redesign

The issues that were identified in the exploring phase, were clustered and prioritized on four aspects using a decision matrix (Figure 123). There were two main issues found in the graphical user interface of the game. One is categorised as medium-priority and one is categorised as low-priority.

Improve the order of steps to take

The usability study of 2022 and the peer tests that were performed during this project discovered **issues in understanding what order of steps needs to be taken prior to using the device**. For example, often participants already donned the device before calibrating it.
It is **advised** to visually make clear what steps are important to take before donning the device to ensure effective and safe use. For example, the first display could show a short overview of all the steps necessary before starting the game and highlight what step is next. Additionally, a progress bar could be added on the bottom to visually represent what is yet to come.

Redesign of the instruction visuals to take the lead over text

During the studies, it became clear that some participants **did not read the instruction text (thoroughly) but performed actions based on the visuals presented on the screen** or their instinct. However, the visuals did not cover the important information that the participants needed to know.
Moreover, it is **discussed with a physical therapist** that a majority of the patients do not have the cognitive capacity to read instructions and act accordingly in a short period of time.
Therefore, it is **advised** that visuals take the lead over text. If the visuals are a perfect visual representation of the textual explanation, they can clearly instruct what is expected from the patient. The visuals can be accompanied by three or four words next to it. This keeps the patients engaged and does not require much effort.

World Haptics Conference

Prior to the demonstration of the hand trainer at the World Haptics Conference, a PhD student from the MLN Lab worked on improving these two issues. The results can be seen in Figure 125 and Figure 126.

	1 t/m5	5=much	5=high	5=much	5=positive	
	Factor	Effort	Costs	Added value	Sustainable impact	Score
	Weight factor	4	3	5	2	
GUI	Improve order of steps to take	2	1	5	3	**55**
GUI	Redesign instructions visuals that take the lead over text	3	1	4	3	**46**

Effort = time and complexity of implementing the improvement
Costs = costs of implementing the improvement
Added value = how much more valuable the end-product would be with the improvement
Sust. impact = an increase or decrease in sustainability of the end-product after implementing the improvement

High-priority
Medium-priority
Low-priority

Figure 123. Decision matrix on the identified problems of the GUI

6.7 Game design

6.7.1 Introduction

This chapter gives **advice** on **the game design** that is used in combination with the hand trainer.

6.7.2 Advice on redesign

The issues that were identified in the exploring phase of this project, were clustered and prioritized on four aspects using a decision matrix (Figure 124). There were five main issues found on the game design that is accompanying the physical device. Three of the improvements have medium-priority and two have low-priority.

Increase short-term engagement

The studies that were performed highlighted that **the game is lacking in short-term engagement**. Short-term engagement is crucial to create a joyful and exciting game experience to increase the will to play it again. This is created by e.g., implementing direct visual and audio feedback based on the user's performance and actions.
It is **advised** to increase engagement by visualising a clear, adjustable goal and implementing rewarding or punishing elements as a direct effect on the user's performance in the game.

Improve visual and audio feedback during game

The participants experienced **lack of feedback on their actions**. This includes actions on setting up the device, donning the device and performing the movements. Next to that, the textual feedback that appeared did not stand out and was often not noticed.
It is **advised** to increase the amount of visual and audio feedback to respond to the user's correct or incorrect actions. It is also advised to complement this with additional haptic feedback. This will contribute to a feeling of engagement from the user towards the game.

Improve haptic feedback

The **haptics** that are used in the game to give feedback on the liquids' different viscosities, was often **not noticed by the participants**.
It is **advised** that the haptic feedback is increased and can be adjusted according to recommendations from the therapist. In this way, the feedback can be personalised per patient.

Improve long-term engagement

Long-term engagement towards a product is important to consider when the user has the

	1 t/m5	5=much	5=high	5=much	5=positive	
	Factor	Effort	Costs	Added value	Sustainable impact	Score
	Weight factor	4	3	5	2	
game	Increase short-term engagement (extrinsic motivation)	2	2	4	3	**47**
game	Improve visual/audio feedback during game	2	1	3	3	**45**
game	Improve haptic feedback	4	1	4	3	**42**
game	Increase long-term engagement	4	3	5	3	**41**
game	Improve engagement with clinic therapy	2	1	2	3	**40**

Effort = time and complexity of implementing the improvement
Costs = costs of implementing the improvement
Added value = how much more valuable the end-product would be with the improvement
Sust. impact = an increase or decrease in sustainability of the end-product after implementing the improvement

High-priority
Medium-priority
Low-priority

Figure 124. Decision matrix on the identified problems of the game design

intention to play the game for a long period of time. The hand trainer is intended to be used for approximately seven days a week, thirty minutes per day. Therefore, it is important to take the long-term engagement into account. Long-term engagement is achieved when patients are still experiencing joy and excitement while playing the game. The majority of the participants emphasised that **the cocktail game is not advanced enough to play on the long-term**, since it does not have much interesting variation.
It is **advised** to include e.g., varying daily goals, variation in tasks using different liquids or different glasses, multiple difficulty levels and multi-player options.

Improve engagement with therapy sessions in the clinic
Currently it is not yet considered to connect the goal of the game to therapy session in the clinic. This could be an interesting way to increase engagement. If patients are familiar with certain things they also use or do in the clinic, they are probably more likely to practice with the hand trainer by themselves.
Therefore, it is **advised** to consider using therapy elements in the game, such as cutting a sandwich or hanging up the laundry and add an exciting twist to it.

World Haptics Conference
Prior to the demonstration of the hand trainer at the World Haptics Conference, a PhD student from the MLN Lab worked on the three medium-priority improvements. The results can be seen in Figure 127 and Figure 128.

Figure 125. Redesigned GUI of introduction pages

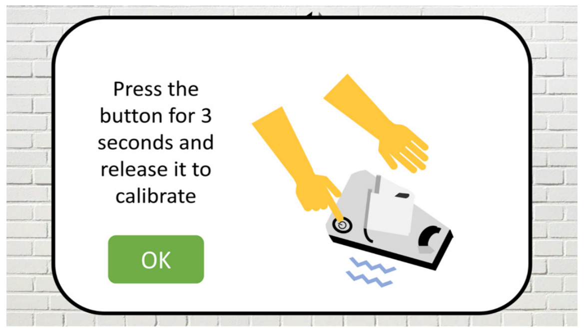


Figure 126. Redesigned GUI of introduction pages

Figure 127. Redesigned GUI of cocktailgame

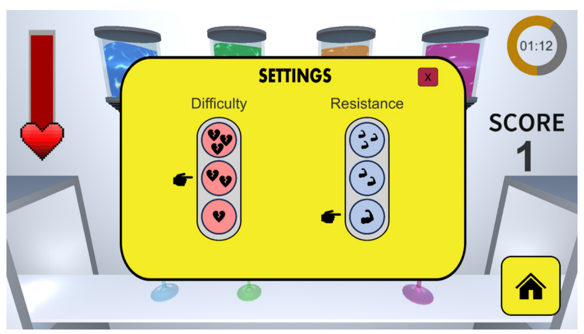


Figure 128. Redesigned GUI of cocktailgame

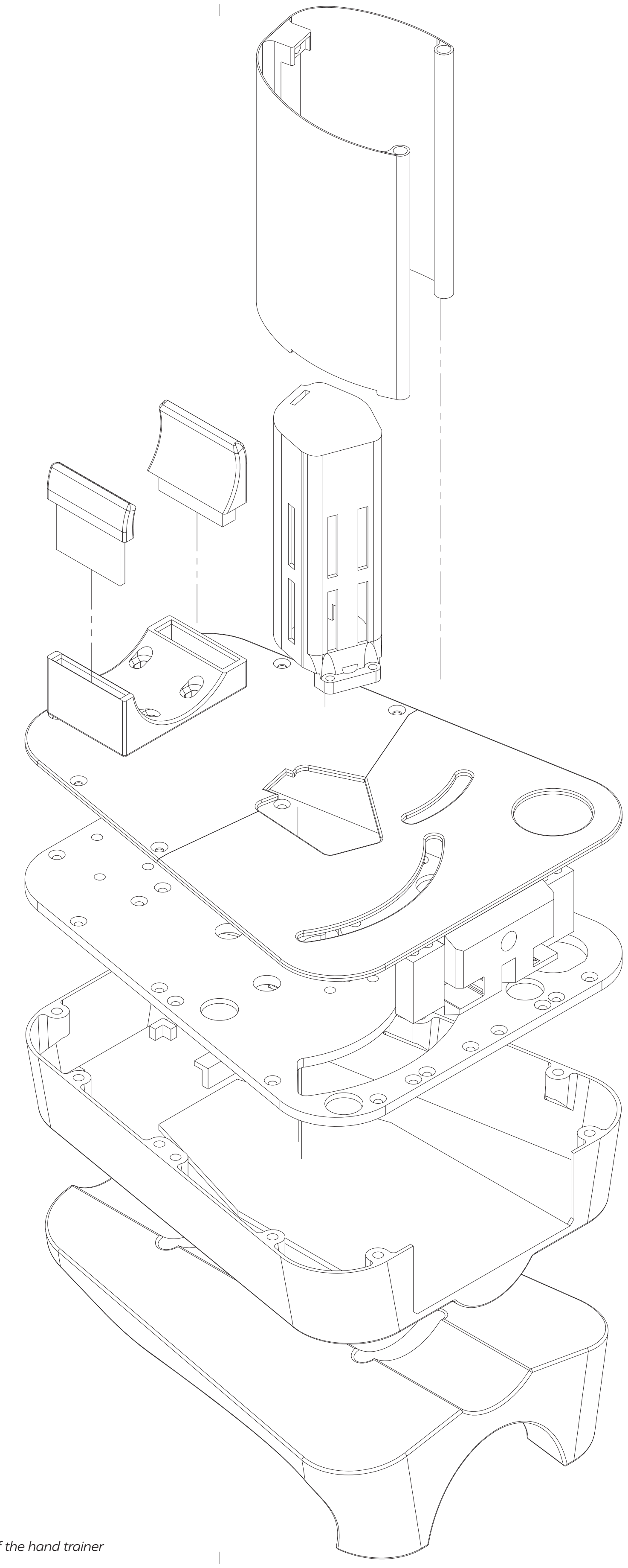


Figure 129. Exploded view of the hand trainer

7 Evaluation

In this chapter, the result of this graduation project, a redesign of the portable hand trainer, is evaluated. The improvements compared to the old design are discussed with experts and evaluated on their feasibility, viability and usability. Further improvements and barriers are discussed to create a future development plan and introduce recommendations in Chapter 9.

This chapter is structured in the following parts:

7.1 Approach

Evaluation of the third iteration of the portable hand trainer

7.1.1 Introduction

This chapter describes the approach used to evaluate the redesign of the portable hand trainer, which is the result of this graduation project. Chapter 7.2 presents the results of the evaluations.

7.1.2 Approach

The redesign of the portable hand trainer is evaluated with four evaluations:

Evaluation 1

One evaluation is performed with an **expert in Biomechatronics**. The redesign is evaluated on the three high-priority improvements with the hardware-ready final prototype.
Method: semi-structured interviewing, 30 minutes

Evaluation 2

One evaluation is performed with a **physical therapist** and an **occupational therapist** from Rijndam rehabilitation center, located in Rotterdam. The redesign is evaluated on the three high-priority improvements with the hardware-ready final prototype.
Method: semi-structured interviewing, 30 minutes

World Haptics Conference 2023

The hardware-ready final prototype was demonstrated at the **World Haptics Conference 2023 at the TU Delft**. For the demonstration, a redesign of the GUI and the game design was connected to the third-iteration-prototype of the hand trainer. Visitors of the conference walked by, tried out the system and described their experience.

Wrist support evaluation

Since the wrist support was not ready before the two evaluations and demonstration took place, the wrist support is seperately and informally evaluated with eight men with varying wrist sizes.

7.2 Evaluation results

An expert in biomechatronics, a physical therapist, an occupational therapist and visitors of the World Haptics Conference 2023

7.2.1 Introduction

In this chapter, the result of this graduation project, a redesign of the portable hand trainer, is evaluated. In **four evaluations**, the improvements on the **high-priority identified problems** are discussed and the results are presented in the following paragraphs.

7.2.2 Evaluation 1

The first evaluation is performed with an expert in Biomechatronics at the TU Delft, focusing on the three high-priority improvements: 1. the pronosupination movement, 2. the wrist support, 3. the donning and doffing. It must be noted that the final prototype of the wrist support was not ready yet, so the prototype of the previous iteration and a 3D digital model on the final iteration were used.

Pronosupination movement:

> The pronosupination movement is mechanically working well.
> Ideally, the rotation point of the device lays on the longitudinal axis of the forearm, but in the current design, the patient needs less force to rotate which is beneficial.
> The dynamic part is unstable, so while performing flexion and extension, the patient also needs to focus on their pronosupination.

The wrist support:

> This iteration of the wrist support is not working well yet. The wristbands are rather disturbing than helping.
> It might be the case that support is not even necessary on the medial side of the wrist. This could for example result in a V/U-shaped wrist support, without support on the top.

Donning and doffing:

> Mechanically, the cone is working well. The hand intuitively slides down and ends around the shell.
> It is contradictory that the cone is not easy to attach to the shell, which is a point of attention.
> The idea of adding a helical shape to guide the hand in the right position may be promising, but adapting the conical shape could also work.

The complete evaluation can be found in Appendix J1.

7.2.3 Evaluation 2

The second evaluation is performed with a physical therapist and an occupational therapist from Rijndam rehabilitation center, focusing on the three high-priority improvements. Again, it must be noted that the final prototype of the wrist support was not ready yet, so the prototype of the previous iteration and a 3D digital model on the final iteration were used.

Pronosupination movement:

> The 10-degree pronosupination rotation is beneficial for patients, so they do not exceed their capabilities.
> Ideally, the pronosupination rotation is performed around the longitudinal axis of the forearm. However, this design isolates the movement much better than the previous design.
> It would be good to extend the body to create slightly more support under the forearm.

The wrist support:

> The wrist support system is not working well yet.
> The bottom support is good, it will probably fit

many wrist sizes since thicknesses of human wrists do not vary much.
> The support on the dorsal side of the wrist is effective.
> The wristbands do not have to extend as much inward as they currently do. Patients do not need support on the medial side of the wrist if ulnar and radial deviation is not stimulated by the system.

Donning and doffing:
> It is fine if the unaffected hand helps the affected hand to reach the right position around the shell and in the wrist support.
> The forearm most likely ends up on the right side of the wrist support.
> It is contradictory that the cone itself is not easy to attach to the shell.

The complete evaluation can be found in Appendix J2.

7.2.4 World Haptics Conference 2023

The third evaluation is performed at the World Haptics Conference 2023 at the TU Delft (Figure 131), focusing primarily on the use of the complete system: **the prototype of the redesign in combination with the redesign of the game and the GUI**. The system was used by multiple visitors of the conference that were shortly introduced to the goal of the device and its development stage.

Results:
> The pronosupination movement worked well mechanically. However, the majority of the users experienced difficulty with switching between cocktail bottles because the physical midpoint/ starting point of the dynamic part on the static part is not clear while using the device.
> During rough usage of the device, the dynamic part slips away from the static part.
> For some users, it was not clear that the thumb must be placed on the left side of the shell.
> The bottom support does not give enough support without the wristbands. The foam is comfortable.

Figure 130. IEEE World Haptics 2023 logo

Figure 131. World Haptics Conference set up

7.2.5 Wrist support evaluation

The wrist support has been designed to fit varying wrist sizes. P75 of the male wrist circumference has been used to calculate the inner dimensions of the wrist support (Chapter 5.2.3). The wrist support prototype was not ready at the two evaluations and the demonstration, so a seperate, informal evaluation was done to evaluate comfort and the inclusivity of varying male wrist sizes.
Eight men with varying wrist sizes were asked to place their wrists in the wrist support, as demonstrated in Figure 132.

Results:
> The wrists of all men that were asked fitted in the wrist support.
> The men emphasised that the wrist support is preferred to be moved a bit towards the elbow, because it is slightly poking at the ventral side of the wrist.
> The flexible wristbands' material is experienced as slightly uncomfortable, since the surface is rather rough.

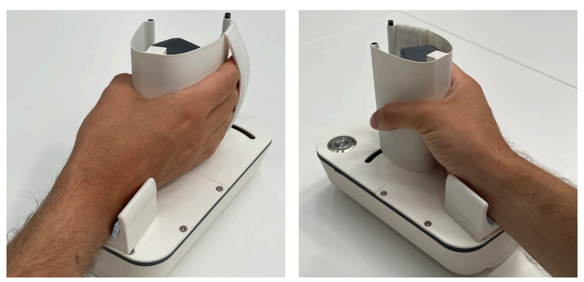


Figure 132. Wrist fit in the wrist support of peer

8 Conclusion

This chapter briefly concludes this master thesis by reflecting on the project and the assignment to evaluate whether the project goal is reached. Recommendations for future work are presented in Chapter 9.

This chapter is structured in the following parts:

8.1 Discussion and conclusion

Reflecting on the goal of the project

8.1.1 Introduction

This chapter concludes the report of this master graduation project. It starts with a brief reflection on the starting point of the project and reflects on the project goal by discussing each of the three high-priority improvements.

8.1.2 Starting point

The starting point of this graduation project was the second iteration of the portable hand trainer, a combination of the physical device and the cocktail game.

Project goal
The goal of this project was to **deliver a hardware-ready, improved product design** of the portable hand trainer in comparison to the second iteration to enable more **functional**, **ergonomic**, and **motivating** rehabilitation training.

8.1.3 Pronosupination movement

The problem
The first identified problem that was categorised as high-priority was the **unnatural and non-isolated pronosupination movement**.

The redesign
To achieve a pronosupination movement that is as isolated and pure as possible, the physical device is tilted under **a 12-degree angle** and transformed into a **two-part design**. In this way, the pronosupination rotation is almost perfectly performed along the longitudinal axis of the forearm.

In the final prototype, the pronosupination movement is mechanically working well, however, a few concrete recommendations for future work are described in Chapter 9.

8.1.4 Donning and doffing

The problem
The second identified problem that was categorised as high-priority was the **unfeasible donning and doffing** of the device for stroke patients.

The redesign
To achieve a feasible donning and doffing situation for stroke patients, **an additional, conically shaped part is added** to the physical device that allows patients that are unable to don from the front of the device, to don from the top of the device.

In the final prototype, donning is well supported with the addition of the cone. The cone is also rather easy to attach. Surely, the design of the cone can be improved, so recommendations are described in Chapter 9.

8.1.5 Wrist support

The problem
The third identified problem that was categorised as high-priority was the **not easy-to-use wrist support** with a **lack of consideration in donning and doffing** for stroke patients and a **lack of consideration in ergonomics**.

The redesign
To achieve an easy-to-use, ergonomically and donning-friendly wrist support, the support has become a **two-part design** with one rigid and two flexible parts. **The support is primarily switched to the dorsal side** of the wrist and the **support at the lateral side of the wrist is largely removed**.

Lastly, the depth of the support is decreased by 10 mm.

In the final prototype, the assistance during donning and doffing of the device is increased and cognitive load is decreased for patients in comparison to the second iteration. The wrist support is increased in ease of use and is ergonomically friendly. The final prototype of the wrist support is not properly evaluated with experts in the field, so this is part of future work, further described in Chapter 9.

Figure 133. Third iteration of the portable hand trainer

8.1.6 Conclusion

The goal of the project was to deliver a hardware-ready, improved product design in comparison to the second iteration to enable more functional, ergonomic, and motivating rehabilitation training. Reflecting on the redesigns of each of the high-priority improvements and the 3D final prototype that is built, it can be stated that the goal of this project is reached. The third iteration of the hand trainer is an improvement on the second iteration of the hand trainer (Figure 133).

8.1.7 Requirements check

The list of requirements for the redesign of the hand trainer, that is proposed in Chapter 4.5, is evaluated below. The majority of the requirements are **met**. Two of the requirements are **not met** yet and one requirement is **partially met**. They require more time and effort in the next stage of the development process, as discussed further in Chapter 9.

- be used by stroke patients who are paralysed on the right side of their body **- met**
- be used by stroke patients that are in Brunnstrom (FMA) stage II-IV **- met**
- be used by stroke patients with a spasticity level of 0,1, 1+ or 2 according to the MAS scale **- met**
- facilitate donning and doffing by stroke patients in the above-mentioned criteria **- met**
- be used by stroke patients independently, but with minimal supervision of a therapist **- met**
- fit hand and wrist sizes of male and female adults from 18-85 y/o using P10-P90 **- met**
- be used approximately 30 minutes per day, 7 days per week **- not met**
- meet CE certification regulations for medical devices **- not met**
- be easily transferable from the rehabilitation clinic to a patient's home with assistance **- met**
- be used in inpatient and outpatient care of the rehabilitation process **- met**
- show improvement in the rehabilitation process of the patient **- met**
- fit within the rehabilitation program of stroke patients **- partially met**

9 Recommendations

This chapter gives recommendations on the future work of the project by reflecting on what is reached and what was scoped out. The chapter finished with a brief roadmap for the near future.

This chapter is structured in the following parts:

9.1 Recommendations

Recommended future work for the development of the portable hand trainer

9.1.1 Introduction
This chapter presents recommendations from the researcher's perspective for future work on the development of the portable hand trainer.

9.1.2 Pronosupination
P1. During the demonstration at the World Haptics Conference, it became clear that there is no clear midpoint while performing pronosupination, either physically or by using haptics. This is recommended to add before performing an extensive usability test with stroke patients to eliminate misunderstanding.

P2. It is recommended to transform the two-part design into a single-part design again to increase stability and portability. It is important to make sure the device is not rotating to one side by itself but has a stable position in the middle.

P3. It is also recommended to optimize the pure pronosupination movement by enabling rotation around the longitudinal axis of the forearm. Whether the pronosupination angle should be increased to > 10 degrees, is depending on the outcome of the extensive usability tests with stroke patients. During the evaluation with therapists from Rijndam, it was concluded that a maximum of 10 degrees also has advantages.

P4. Since supination is more important to practice than pronation, it is recommended to create an asymmetric design that has lays focus on supination than pronation. It is recommended to also implement this in the game design.

P5. It is recommended to create more support under the distal part of the forearm by extending the base of the device to increase comfort during use.

9.1.3 Donning/doffing
D1. Regarding the cone, it is recommended to improve the attachment of the cone on the shell based on the results from the extensive usability test with stroke patients.

D2. It is also recommended to continue optimising the shape of the cone to reach an optimal shape that is positioning the forearm as efficiently as possible.

D3. The cone is currently designed for the medium-sized shell. It is recommended to redesign the cone to a universal design that fits on all three shells.

9.1.4 Wrist support
W1. It is recommended to continue experimenting with different types of materials for the wristbands that fulfill all the requirements, since 3D printing can most likely eventually not be used in a rehabilitation device at Rijndam rehabilitation center.

W2. The design of the wrist support is currently based on a wrist circumference of 30-79 y/o males, using P75. Large scale testing with stroke patients with varying wrist sizes is recommended to evaluate inclusivity.

9.1.5 The complete system
S1. An extensive usability test with stroke patients of the target group using the third iteration of the hand trainer, is planned in the beginning of 2024. It is recommended to implement the majority of the previously mentioned recommendations as much as possible before the usability test to gain as much valuable results as possible.

S2. Prior to the usability study, it is recommended to integrate visualisations of the third iteration in the GUI of the game and adjust the GUI and the game to the adapted functionalities of the third iteration.

S3. After the usability study, is it recommended to do in-depth research on suitable materials for the parts of the product that are not yet medically certified.
Additionally, it is recommended to do research on suitable production processes for the 3D printed parts.

9.1.5 Decision matrix
In the defining phase of this graduation project, a decision matrix was used to prioritise the possible improvements on the hand trainer. This graduation project primarily focused on the high-priority improvements.

M1. It is recommended to continue prototyping and evaluating the ideas for the medium-priority improvements.

M2. It is also recommended to start ideation and prototyping on the low-priority improvements. Some of these improvements had high added value but would simply take too much effort to tackle within this graduation project.
Figure 134 shows the medium- and low-priority improvements in the decision matrix.

	1 t/m5	*5=much*	*5=high*	*5=much*	*5=positive*	
	Factor	Effort	Costs	Added value	Sustainable impact	Score
	Weight factor	4	3	5	2	
device	Improve on/off button functionality	1	1	2	3	**44**
device	Redesign emergency buttons functionality	2	2	2	4	**39**
device	Improve finger placement and ergonomics of the shell	3	2	3	3	**38**
device	Improve connection of cables	4	1	2	4	**34**
device	Accommodate adjustable positioning of the wrist support	3	2	2	3	**33**
device	Include left hand usage	5	4	5	2	**32**
device	Include independent movement of fingers	4	3	3	2	**29**
game	Increase short-term engagement (extrinsic motivation)	2	2	4	3	**47**
game	Improve visual/audio feedback during game	2	1	3	3	**45**
game	Improve haptic feedback	4	1	4	3	**42**
game	Increase long-term engagement	4	3	5	3	**41**
game	Improve engagement with clinic therapy	2	1	2	3	**40**
GUI	Improve order of steps to take	2	1	5	3	**55**
GUI	Redesign instructions visuals that take the lead over text	3	1	4	3	**46**
combi	Improve cleanability	2	1	4	4	**52**
combi	Improve sustainability	2	2	4	5	**51**
combi	Wirelessness of device	4	2	5	4	**46**
combi	Usage without prior instructions from therapist	1	1	2	3	**44**
combi	Improve coherency between design of software and embodiment	3	3	2	3	**30**

Effort = time and complexity of implementing the improvement
Costs = costs of implementing the improvement
Added value = how much more valuable the end-product would be with the improvement
Sust. impact = an increase or decrease in sustainability of the end-product after implementing the improvement

High-priority
Medium-priority
Low-priority

Figure 134. Decision matrix of the defining phase: medium- and low-priority improvements isolated

9.2 Roadmap

A 2-year roadmap with future steps to implement the recommendations

9.2.1 Introduction

This chapter presents a 2-year roadmap with future steps to implement the recommendations presented in Chapter 9.1. The presentation of this master thesis is the starting point.

9.2.2 Roadmap

The roadmap is visualised in Figure 135. The different colors and abbreviations represent respectively the different subchapters and recommendations that are discussed in Chapter 9.1. The roadmap is primarily based on the envisioned deliverables for each of the usability tests. The recommendations with highest priority (P1, P3, D1, D3 and S2) must be addressed before usability test 2 (S1). The recommendations with lower priority (P2, P4, P5, D2, S3, M1 and M2) can be addressed after usability test 2.

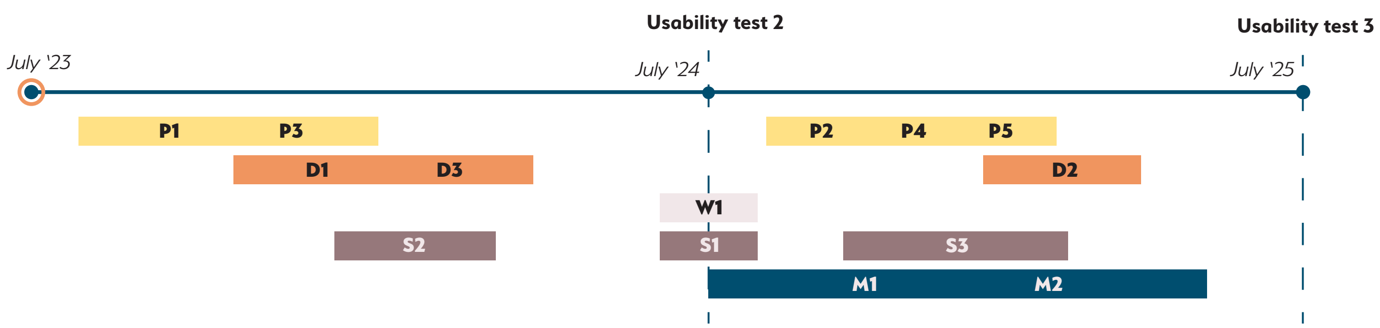


Figure 135. 2-year roadmap for implementation of the future recommendations

Personal reflection

This chapter reflects on the master thesis from a personal view by reflecting on the project assignment, the project approach, the goal and final result, the supervision, personal growth and future steps. The personal reflection closes off this master thesis.

This chapter is structured in the following parts:

Reflect

Personal reflection

When I started this graduation project in February, it was clear to me that it was a good fit. The chance to develop a redesign for an emerging medical device appeared to be the ideal opportunity to reach my personal learning goals (**LG**s).

LG1. With many thanks to the good collaboration between the Lab and Rijndam rehabilitation Center, I was able to go to the clinic multiple times and expand my knowledge about the effects of a stroke incident and the heterogeneous rehabilitation process afterward by comparing it to my desk research.

LG2. The goal that was set in this project, to deliver a hardware ready 3D final prototype, stimulated me to do a lot of rapid-prototyping and increased my experience with modelling in Fusion 360, 3D printing, silicon molding and resin printing with varying materials.

LG3. I was able to host a hybrid co-creation session with the Focus Group that we set up at the beginning of the project. It not only resulted in a lot of valuable feedback, I also learned a lot about hosting a stakeholder session efficient and effective.

LG4. At the beginning of the project, an application for a non-WMO (medical) request was started to get approval to test with the target group at the end of the project. After a few months, it was disappointing to find out that we were not able to do a formal test with people after stroke. Therefore, I did not learn as much in preparing and performing extensive user testing as I had in mind beforehand. However, by analysing the usability study results, performing the peer tests and hosting the Focus Group session, I did gain knowledge about extensive preparation of usability tests to effectively and efficiently gather valuable data.

LG5. By setting the goal to develop a hardware-ready final prototype, I stimulated myself to dive into the mechanical and electronic components that are necessary to enable the functions the hand trainer has. It was interesting to see how the constraints of the interior design has influenced the project.

Finally, it stood out to me that I much enjoyed managing my own project. Arranging and preparing meetings with important stakeholders and experts but also keeping the supervisory team on the same page by sending weekly-updates. It helped me to stay on track. These were also the moments to realize what I had achieved so far already and what I had learned.

Figure 136. Third iteration of hand trainer in use

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