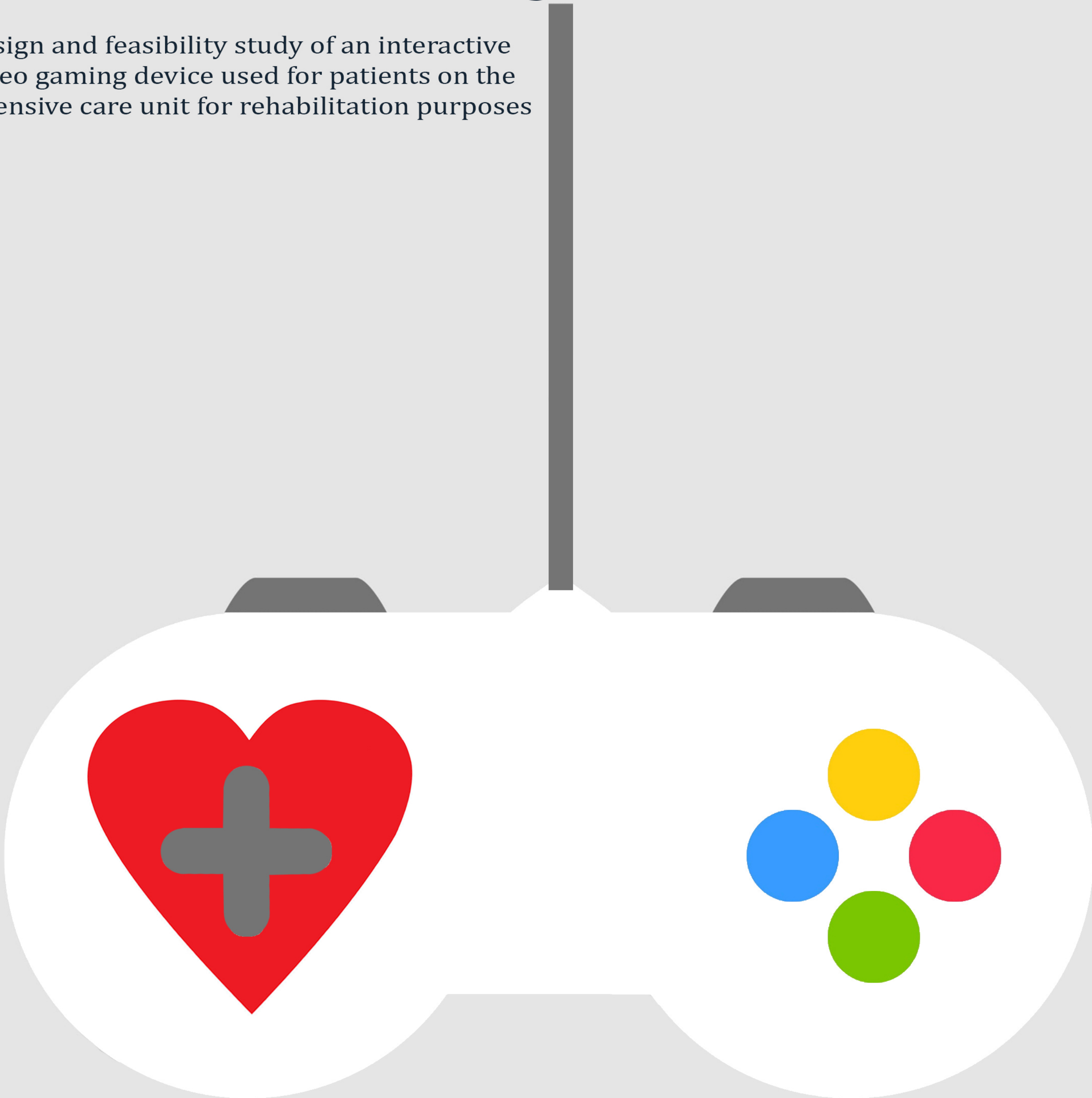
Interactive Video Gaming on the Intensive Care Unit

Design and feasibility study of an interactive video gaming device used for patients on the intensive care unit for rehabilitation purposes



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Interactive Video Gaming on the Intensive Care Unit

Design and Feasibility Study

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to obtain the degree of Master of Science
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***“Life is more fun
if you play games.”***

Roald Dahl, 1980, ”My uncle Oswald”, P.128, Penguin

Abstract

Admission to the intensive care unit often has long lasting effects on patients' further life. Not only can the reason for their admission leave several problems, but also mechanical ventilation, physical inactivity, sedation and delirium are only some of the factors that contribute to the problems left after ICU stay. Over 80,000 people are annually admitted to the intensive care units of the Dutch hospitals alone and, due to technical advancements, a rising number of patients survives critical illness.
Post intensive care syndrome is the overarching name that combines all the physical and mental problems related to intensive care unit stay. It has been well established that rehabilitation and early mobilisation are effective countermeasures against post intensive care syndrome. It has also been shown that interactive video gaming can play a useful role in rehabilitation as an addition to conventional therapy. Evidence has shown that the use of visual feedback improves performance and adherence to the therapy in comparison to regular of physical therapy. This design study is meant to create a new interactive video gaming device that allows ICU patients that are at least semi mobile and semi cooperative, to play video games with the aim to help them leave the ICU in the best physical and cognitive state as possible.

To come up with the right design, a literature study on the relevant subjects has been done. Also, expert interviews with intensive care unit care-giving staff have been conducted and experience has been gained on the intensive care unit of the Erasmus medical center Rotterdam to make sure the design is done in the right context. Based on the outcomes of this research the decision was made to aim the design to help in activities of daily living. From this aim a specific goal was formulated:

The goal is to create an interactive video game controlling system that allows ICU patients, that are at least semi mobile and semi cooperative, to play video games that simultaneously helps in increasing muscle strength, delivers distraction from the daily routine in the ICU and stimulates patients cognitively.

Together with physiotherapists and intensivists from the Erasmus medical center Rotterdam a list of requirements for the final designs was created. As during activities of daily living hand grip is one of the most important aspects, the decision was made to use sub-maximal grip force control as the desired training form. Because of this two different versions of grip strength trainers were proposed. The first concept uses the medium wrap grasp as input movement and the second concept uses the power-sphere grasps. These are two of the most frequently used grasp types in daily life. The concepts are designed in a way that the force exerted on the device can be used to control a video game. Internal force sensing resistors, connected to an Arduino, translate the force to a useful signal to control the game. Ten prototypes were created to get to the final designs, which were then tested with patients on the ICU.

As result of testing and iterating the concepts, two final designs were delivered, fulfilling the list of requirements. Feasibility tests of these designs were done on the ICU of the Erasmus medical center Rotterdam and were promising. ICU patients participating in the tests understood the game well, were capable of performing the required movements to play the game and delivered feedback on the design and the gaming experience.

This paper has lead up to a final prototype that has gone through basic testing to check for feasibility and has proven to work. Further scientific research on a larger scale should be the next step to review the clinical effects of the device.

Terms	
3D printing	the construction of a three-dimensional object from a CAD model
Around-the-clock	24 hour per day service
Arduino	Open-source electronic prototyping platform enabling users to create interactive electronic objects
Critically ill patients	Patients admitted to the ICU
Early mobilisation	Rehabilitation of patients started during the first days of hospital admission
ECMO	Apparatus that takes over both heart as well as lung functioning
Edema	fluid retention or swelling, is the buildup of fluid in the body's tissue
Ergometer	Apparatus which measures work or energy expended during a period of physical exercise
Exergames	Games used for exercise. Combination of exercise & gaming
Glascow coma scale	Scale used to score a patient's level of sedation
Hand dynamometer	Apparatus used for measuring grip strength
Mechanical ventilator	Apparatus that takes over or supports lung function
Metacarpophalangeal (MCP) Joint	Finger joints between metacarpals and proximal phalanges
Proximal Interphalangeal (PIP) Joint	Finger joints between proximal phalanges and middle phalanges
Rehabilitation	care arimed at improving abilities needed for daily life
Silverfit	Partner company during graduation, specialised in making exergames for elderly
Tonus	Continuous and passive partial contraction of the muscles

Table 1: Terms

Abbreviations	
ADL	Activity of Daily Living
ADLS	Activities of Daily Living Scale
APA	American Psychiatric Association
AZR	Academisch Ziekenhuis Rotterdam (Academic Hospital Rotterdam)
CAD	Computer-Aided Design
CCU	Critical Care Unit
DSM-V	Statistical Manual of Mental disorders
ECMO	ExtraCorporal MembraneOxygenation
EMC	Erasmus Medical Center Rotterdam
EMG	ElectroMyoGram
FSR	Force Sensing Resistor
GCS	Glascow Coma Scale
ICU	Intensive Care Unit
ICUAW	Intensive Care Unit Acquired Weakness
IMU	Internal Measurement Unit
IV	IntraVenous
Kg	Kilogram
MCP	MetaCarpoPhalangeal
MRC	Medical Research Council
MRC-SS	Medical Research Council Sum Score
N	Newton
N.d	Not defined
PICS	Post Intensive Care Syndrome
PICS-F	Post Intensive Care Syndrome-Family
PIP	Proximal InterPhalangeal
PLA	PolyLactic Acid
PTSD	Post Traumatic Stress Disorder
QOL	Quality Of Life
RIVM	Rijks Instituut voor Volksgezondheid en Milieu (National institute for public health and the environment)
ROM	Range Of Motion
UK	United Kingdom
VR	Virtual Reality

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Preface

This is the report of my research into the design of an interactive video gaming device to be used for rehabilitation purposes of intensive care unit patients. The research was executed in collaboration with SilverFit and the Erasmus Medical Center Rotterdam (EMC). The thesis is part of the Biomedical Engineering master program of the Delft University of Technology. It was carried out from December 2019 until September 2020 in Woerden (location of the office of SilverFit), Delft (location of the Delft University of Technology) and Rotterdam (location of the Erasmus Medical Center Rotterdam).

By completing this thesis, I am also finalizing my long but fun period as a student of the Delft University of Technology. First as a bachelor student in Mechanical Engineering, with a little sidestep to Industrial Design, later as a master student in Biomedical Engineering with a specialisation in biomedical devices. In my final thesis I got to use all of the experience gained in mechanical engineering and biomedical engineering. But I also got to use the experiences gained at industrial design once again.

Completing my graduation project has been complicated quite a bit by the Covid-19 or corona virus. The first pandemic most of us have ever experienced, made the project's progress slower than I would have liked and had me looking at different approaches to reach the final goal. Not being able of being present at either SilverFit or the ICU of the EMC made things a lot more complicated as progress and the ability to test slowed down. The lockdown also hampered the amount of time that could be spent with testing of the concepts. By choosing different routes and with some help from outside I have managed to create a final thesis as well as a fully functioning prototype that I am proud of.

First and foremost I would like to thank all the staff of the Erasmus Medical Center Rotterdam Intensive Care Unit for giving me the opportunity to carry out my study there, for giving me the space and help needed and for the extraordinary experiences I otherwise would have never had. Also I would like to thank my graduation thesis advisors Jaap & Elif for their help and guidance through this period, especially all the calls with Elif to help me put structure in my processes. Also I would like to thank everyone at SilverFit for providing the project.

Lastly but most of all, I would like to thank Louise for her help, support and encouragement to get through my graduation project in a tumultuous time. Without you it would have been so much harder at times to find the motivation to finish this project.

Philip Oomkens
Rotterdam, August 2020

Contents

1 Introduction

Each year around 80.000 people are admitted to one of the Dutch Intensive Care Units (ICUs). These 80.000 patients, of whom $\frac{1}{3}$ is admitted to the ICU because of planned surgery, $\frac{1}{2}$ for severe medical problems and the rest because of emergency surgery or other reasons, usually only stay in the ICU for a few days. However, even though the majority of patients will leave the ICU rather quickly, there is still a large number of patients that will stay there for weeks or even months. Next to that, there is a large number of patients leaving the ICU that can not be mobilised for days or weeks because of severe muscle weakness after ICU discharge. It is hard for physiotherapists to get these people to rehabilitate, exercise and move as much as they should.

The number of patients that survive critical illness increases with technical and medical advancements in care-giving. This expanding group of survivors brings an increase in additional care needed. Elderly patients are already the most represented group of patients on the ICU and because of the aging population, the need for intensive care is most likely only rising in the next years.

The ICU already accounts for up to 20% of the total costs of a hospital (Moerer O., 2007), even though it is far from the biggest department in hospitals. Unfortunately we can not decrease the need for intensive care. What we can try to do is decrease the time people spend on the ICU and improve the patient's physical and mental state when they get discharged from the hospital.

1.1 Intensive Care Unit

The intensive care unit is a separate part of the hospital, specialised in patients who have life-threatening conditions and need around-the-clock surveillance and/or life support. Usually there is at least one nurse per patient on the ICU during the day, and at least one nurse per every two patients during the night, however this may vary per hospital. ICU rooms are often equipped with a wide vary of machines, most commonly being a heart monitor, mechanical ventilator and intravenous (IV) syringe pumps. Dialysis and ECMO machines are also commonly available, but are not standard equipment in every room. Figure 1 shows a lot of the devices that might be present in a patient's ICU room. It may also give a clearer idea of how many wires, tubes and devices are connected to the patient.

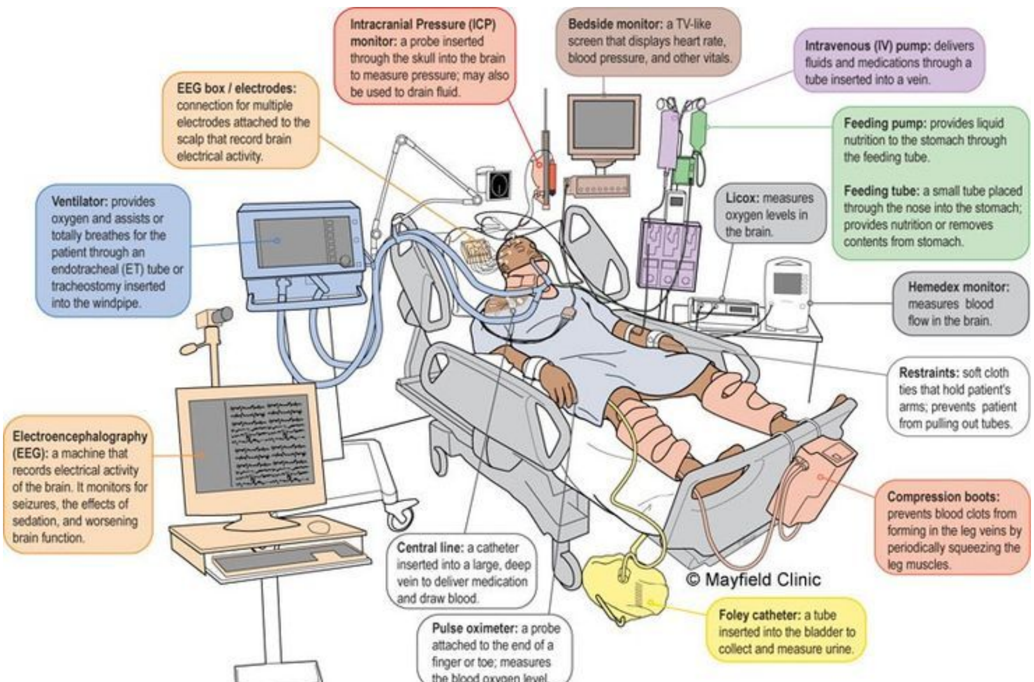


Figure 1: ICU room devices

The reasons a patient might be admitted to the ICU differ immensely, it can be anything from a life threatening -sometimes contagious- disease, severe trauma from an accident, recovery from a major surgery, a serious infection (e.g. sepsis, pneumonia) to any other life threatening state that a patient is in. This means that the ICU staff has to be specialised in a wide range of conditions and be able to react to many different situations. However, to counteract this need for such a broad specialisation, most large hospitals have different intensive care units for different patient groups.

1.2 ICU patient

As the reason a patient is admitted to the ICU varies so strongly, there is no one general type of ICU patient. Age, sex, illness severity, reasons for admission to the ICU, mental health, cognitive state and many more factors can be used to differentiate a patient. Large hospitals often have multiple ICUs for different types of patients; i.e. cardiac ICU, surgical ICU, pediatric ICU. Smaller hospitals often have a more generalised ICU, but often use co-operations with other health institutes that do offer more specialised care for critically ill patients.
With an aging demographic, the age of the average ICU patient is also rising and higher age has been associated with a higher mortality rate in ICU patients. As Creagh-Brown B, 2014 studied, the average age of ICU patients has increased by 4.4 years between 1993 and 2003. By 2013 the median age of ICU patients in the UK was 66 and there is a group of 15% of all patients that are now over 80 years of age, which is a 36% increase since 1993. Because of an aging global population, this average and median age is likely only increasing in the next years.

1.3 Post intensive care syndrome

Post intensive care syndrome (PICS) is the overarching name that combines all physical, psychiatric and cognitive disabilities that develop during intensive care stay. 30 to 80% of ICU patients will develop PICS during their ICU stay. Intensive care unit acquired weakness (ICUAW), severe muscle weakness as a consequence of ICU stay, is the most easily noticeable part of PICS. Physical inactivity increases the risk of muscle weakness, delirium and prolonged mechanical ventilation, which in term are the main risk factors for ICUAW.
PICS often has effects that can be seen for years after ICU discharge. Depending on the cause of the ICU admittance, 15% or more of all patients suffer from severe Post Traumatic Stress Disorder (PTSD)v [Griffiths J., 2007], anxiety, depressive thoughts or nightmares or have problems with concentration. Next to that the physical aspect of PICS leaves patients weak and often not capable of returning to their daily routine. 50% of patients that leave the ICU can not return to their work one year after ICU discharge and a large number of those patients might not ever return to the job they had before they were admitted to the ICU. for these reasons ICU admittance often has a large impact on the perceived Quality Of Life (QOL) after discharge from the hospital.

1.4 Post intensive care syndrome-family

The admission of a family member, suffering from a critical illness, on the ICU, can have adverse psychological effects on the rest of the family. Anxiety, acute stress disorder, depression and complicated grief are complications that can occur from exposure to critical care. This cluster of complications is called post intensive care syndrome-family. Not only patients on the ICU, but also their relatives and loved ones, can feel the effects of an ICU admission, which may carry on for up to 4 years after discharge. These psychological effects may hamper the family member's ability to fully engage and provide in necessary care giving roles after hospitalisation[Davidson JE, 2012]. Clinically relevant anxiety (including stress disorders and PTSD symptoms) as well as clinically relevant depressive symptoms are common in family members of patients who have been critically ill, and may decrease over time [Azoulay E, 2005,Jones C, 2004].
Communication between healthcare workers and family members and involvement of the family in care and decision making may affect long term outcomes. A family member's involvement in daily routines and seeing improvements in the state of the patient may beneficially effect PICS-F. Getting family to help in rehabilitation exercises may contribute to this as well.

1.5 Early mobilisation

Early mobilisation is defined as mobilisation of the patient within the first 2-5 days of ICU admission. Early mobilisation strategies in the ICU can help in the prevention and reduction of ICUAW, may improve QOL, functional mobility at hospital discharge shorten ICU and hospital stay and can reduce mortality during ICU stay. Many factors like age, the used protocol, illness severity and many other may however influence the results of early mobilisation. From many studies [table 3] the consensus has been reached that patient specific early mobilisation protocols have positive effects on the patient's well being during and after hospital stay.

1.6 Gaming as rehabilitation

A major barrier in rehabilitation is patient non-adherence to their therapy. Not meeting a sufficient amount of movement required to induce neuroplastic adaptations underlying behavioral improvement [Lang CE, 2009], can lead to increased chances of ICUAW, prolonged rehabilitation and increased mortality. The lack of intrinsically motivating forms of rehabilitation has been one of the main reasons to start with the adaptation of interactive video games in early mobilisation. Over the last years research has suggested that video games are beneficial for both cognitive and physical functioning of critically ill patients. Interdisciplinary evidence suggests that factors like game design, rewards and goals to achieve lead to increased motivation and engagement. One of the clearest examples is in bed-cycling with and without visual feedback for the patient. Visual feedback showed to increase both the play time as well as the physical performance of the patient.

1.7 SilverFit

SilverFit is founded in 2008 with the goal to make life more pleasurable for the elderly by making use of innovative technologies. This goal is fulfilled by making physical activity more enjoyable, for instance during rehabilitation, by making use of computer games.
It all started with their first system, the silverfit 3D, released in 2009, which made use of a 3D camera system to track motions of people standing in front of a screen. The system was meant for elderly to play easy games, without being hampered by a lack of technical understanding or capability to use complex computer gaming devices. It was also designed to take into account some physical problems elderly people might have, and the fact that they are usually less mobile and move slower than the usual target audience that the gaming companies design for.
From the small two-person start up it was back in 2008, SilverFit now has over 40 employees creating products that are being used in 22 countries, throughout over 4000 different locations.

1.8 Erasmus Medical Center Rotterdam

The Erasmus Medical Center Rotterdam is, both in number of beds as in revenue, the biggest academical hospital of the Netherlands. It started out as a regional hospital in 1839 as the Coolsingel hospital, but fused with the Sophia children hospital to become the academical hospital Rotterdam (AZR) in 1971. In 2002 the AZR fused with three other hospitals, as well as the healthcare faculty of the Erasmus University Rotterdam, to become the Erasmus Medical Center Rotterdam.
During the Covid-19 crisis in 2020 the EMC has been appointed to be the national coordination center for patient dispersion to provide and monitor the number of free ICU beds in the Netherlands. The EMC, together with the RIVM, make up the two expertise laboratories that take care of most of the research against the Covid-19 virus. The EMC is also one of the two academical hospitals that does research on antibodies against the corona virus.

1.9 Design challenge

To explore the possible design characteristics of a new interactive video game system to be used in the rehabilitation and early mobilisation of ICU patients, the following design challenge is defined:

Design of an interactive video game system to be used for counteracting muscle weakness in ICU patients, that may provide extra help in the rehabilitation of both physical as well as cognitive performance of critically ill patients.

1.10 Research structure and methodology

The double diamond design technique has been used for many years as a guideline through design studies. It was originally launched in 2004 by the design council UK [UK, n.d.] to give a simplified and clear visual description of the design process. The two diamonds represent a process in which exploration and focused action follow each other up in the way of divergent thinking and convergent thinking. This way there is a clear pathway from challenge to outcome within a clearly defined method.
The double diamond consists of four different parts, Discover, Define, Develop and Deliver. Figure 2 shows how these parts follow each other and what the main idea of each section is.
In the first diamond the problem is first broadly studied to get a better understanding of the subject and find all information about the relevant topics. Then the scope is converged to find the specific design challenge. In the second diamond there is first a diverging creative phase to come up with possible ideas and solutions for the design challenge, after which diverging leads to concepts of the best usable solution.

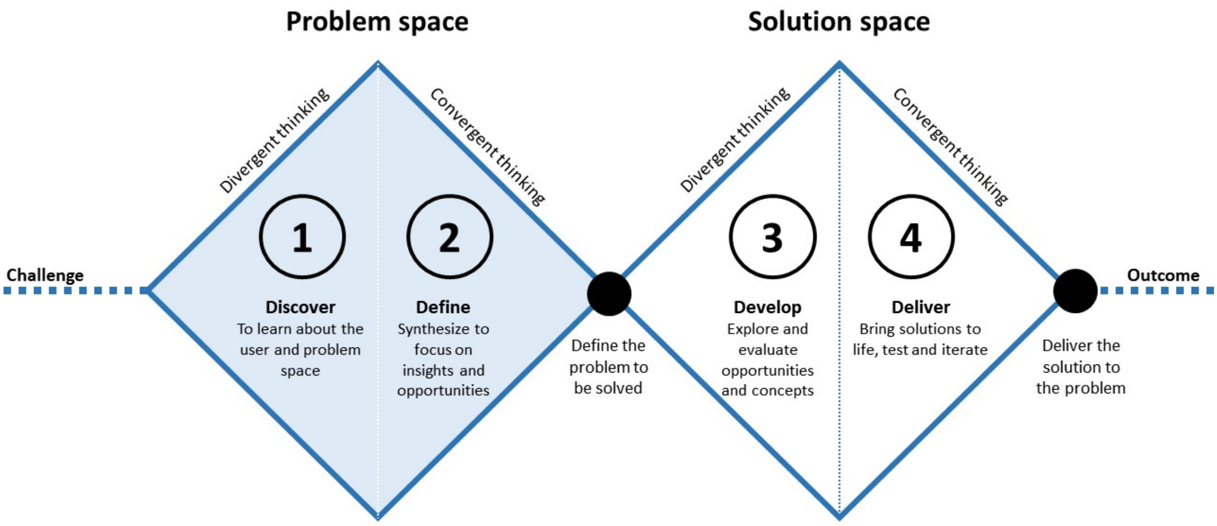


Figure 2: Double diamond design

1.10.1 Discove

The discovering phase is meant to diversify and gain as much knowledge on the topics as possible. It includes the literature review done on the subjects of intensive care unit acquired weakness, early mobilisation of ICU patients and gaming as a form of rehabilitation. Expert interviews have been conducted with ICU doctors, physical therapists and nurses. Next to that, a summary has been made of the real life experiences gained during multiple days carrying along in the daily routines on the ICU.

1.10.2 Define

In the defining phase all knowledge and data gained from the discovering phase will be filtered and elaborated to specify all problems and possible opportunities. Insights will be gained and a good idea of the actual problems is being set up. The goal of the defining phase is to eventually come up with and set the design challenge.

1.10.3 Develop

The development phase will show the design requirements, criteria and the goals that the system has to fulfill. First the MoSCoW method is used to come up with the appropriate list of requirements. MoSCoW is an acronym for Must, Should, Could & Would. It's aim is to create a list of requirements that:

- **M**ust have this requirement to meet the needs
- **S**hould have this requirement if possible, but design success does not rely on it
- **C**ould have this requirement if it does not affect anything else on the project
- **W**ould like to have this requirement later, but delivery will not be at this time

Figure 3 shows the original version and extra explanation of the MoSCoW method.

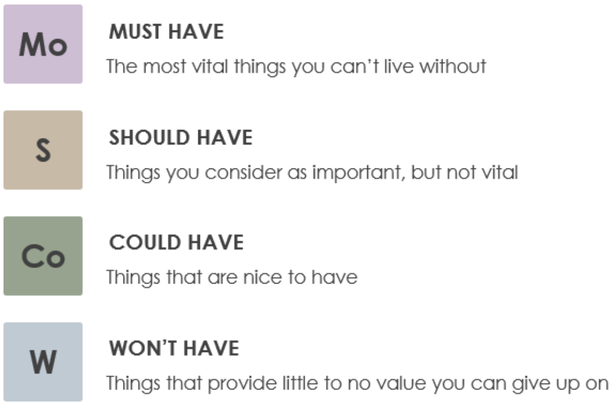


Figure 3: "Moscow Method", n.d.

After the list of requirements has been formed, the next step is brainstorming and broad ideation to gain as many possible ideas as possible. Different options for the exercises are discussed and chosen. Different ways of measuring input are discussed, compared and chosen and preliminary models and concepts are made to test the ideas.

1.10.4 Delivering phase

In the delivering phase the concepts will be manufactured, tested and iterated in real life situations. This system will be repeated until the optimum prototypes are created. The last step of the delivering phase is to capture all that can be learned from the design and iteration steps and to define the results.

1.10.5 Evolve phase

After all the stages of the double diamond design comes the Evolve phase. The results are discussed and conclusions can be drawn based on the outcomes of testing and assessments. Recommendations on implementation and possible further research and testing of other alternatives will be given. The thesis is ended with a reflection on the study.

1.11 Design scope

To find the specific problems a literature study will be done, but also expert interviews will be done with physiotherapists, nursing staff and intensivists of the EMC and the Gelre hospital. As patient opinion might be even more important than the expert view, questionnaires will be held during testing with the patients to contrive what they would like to see in an interactive game.
The assessed design alternatives will be conceptual designs, after which the chosen concepts will be tested to come up with a final design.
The final design will be assessed with patients of the ICU of the EMC Rotterdam, which will involve both measurements of the patient specific results, as well as questionnaires with the patients. These results will be used to asses the design and decide on the feasibility of future work.
The deliverables of the final thesis will be the proposed design combined with a feasibility study to see whether the design works. The goal is not to create an entire product with games, it is to create a device that can be used for playing video games for ICU patients.
A target audience out of all ICU patients will be specified. This is done to keep the results similar throughout the study group, but mostly to be able to design for a specific group instead of designing for alle ICU patients. For this specific target audience we will try to focus on only a few simple movements. The eventual goal for SilverFit is to include a larger target audience and many more movements, but for this study the aim is to include only a smaller part to design for.
There is a large number of patients that feel the physical and mental after-effects of their ICU stay, but little things like playing games or social contact can help these patients in their mental health. Extra exercise of the muscles can help keep ICUAW from setting in and so help patients with their physical health. Combining these two might help patients a lot during their ICU stay, which formulates the goal we want to reach by creating this device;
The goal of the final design is to create a device that can help patients on the ICU with their physical and cognitive health. We want to do this by creating a gaming system which requires the patient to use muscle force as an input and requires cognitive effort to complete the game.

1.12 Approach

To facilitate in the design challenge, a series of design sub questions have been drafted. The goal of these sub questions is to answer the unknowns for each of the 4 design steps from the double-diamond design. Each of these designs steps is meant to finally come up with the best design and the sub questions are meant to give some guidance throughout this design research.

Design sub questions

Discover

1. What are the problems that occur during ICU stay?
2. What is known about the effects of early mobilisation and video gaming as rehabilitation?
3. In what way can video games play a role as an addition to current physical therapy?
4. What new insights can be gained from the care-giving staff on the ICU?

Define

5. What are the barriers to current rehabilitation techniques?
6. In which ways can ICU patients physical and cognitive functioning be scaled?
7. What is the target audience for which the system will be designed?
8. What are the possible movements that can be used as an input for the game?
9. How is gaming currently utilised for rehabilitation on the ICU?

Develop

10. What are the design goals for a new way of controlling video games for ICU patients?
11. What exercises should be used as input?
12. Which system solutions can be defined to translate the input to the game?
13. What are the essential requirements that should be present in the final solutions?
14. What game solutions can be used for the chosen input form?

Deliver

15. What are the required specifications of the final versions?
16. What methods can be used to assess the concepts?
17. How will these assessments affect new design alternatives?
18. What is the proposed final design comprised of?

2 Discover

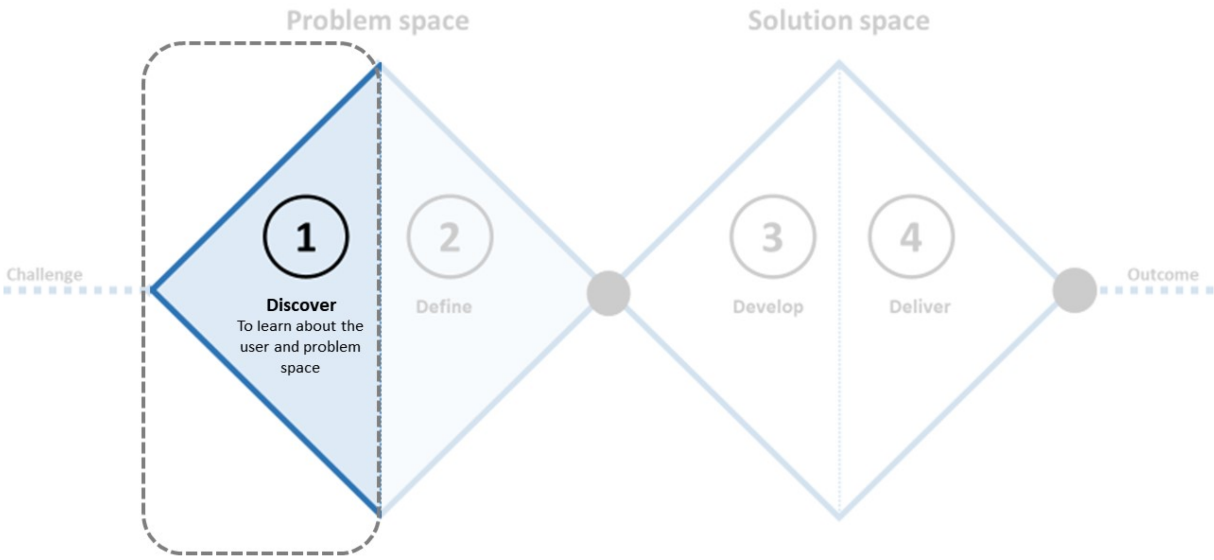


Figure 4: Double diamond design: Discover

The discover phase will answer the following sub questions:

1. What are the problems that occur during ICU stay?
2. What is known about the effects of early mobilisation and video gaming as rehabilitation?
3. In what way can video games play a role as an addition to current physical therapy?
4. What new insights can be gained from the care-giving staff on the ICU?

2.1 Literature review

To fully understand and define the problems and shortcomings of ICUAW, Early mobilisation and gaming as a form of rehabilitation, an extensive literature review is performed. This literature review is meant to elaborately explain the physical and cognitive problems that patients may experience after leaving the ICU, the safety of early mobilisation and the effects it can have on rehabilitation and the way video games are currently implemented in rehabilitation purposes.

2.1.1 Intensive Care Unit Acquired Weakness

Survival from critical illness and discharge from the ICU are often the beginning of an arduous journey to recovery. Prolonged bed rest during sickness or sedation are major contributors to intensive care unit acquired weakness (ICUAW), which can be defined as the clinically identifiable weakness acquired in a critical care setting, directly caused by their critical care state and where other causes of weakness have been excluded [De Letter M.A., 2000]. The diagnosis is made in awake and cooperative patients, by testing their muscle strength and scoring it on the Medical Research Counsil (MRC) sum score [Hermans GMD, 2012]. This severe muscle weakness can be caused by axonal neuropathy, primary myopathy or both. The underlying pathophysiological mechanisms will not be further discussed in this review.

Even though most critically ill patients will experience some sort of weakness from their illness, it is only considered to be ICUAW when a certain severity is reached. When ICUAW is diagnosed, the patient has a constellation of pathologic findings in peripheral nerve and skeletal muscle that has been described as critical illness polyneuromyopathy. This is such a severe weakening of the skeletal muscle that it is considered to be ICUAW [De Letter M.A., 2000]. ICUAW is one of the major causes of extended ICU and hospital stays, elongated duration of mechanical ventilation, post-discharge physical and mental problems, delirium, increased mortality and decreased QOL [Batt, 2017; Bittner, 2009; Herridge MS, 2011; P. M. Schweikert W, 2009].

Known risk factors for ICUAW include illness severity, immobility, old age, electrolyte disturbances, administration of corticosteroid and neuromuscular blocking drugs, and diagnosis of sepsis. Links between sedatives and reduced mobility have also been made [P. M. Schweikert W, 2009]. Next to that, the amount of muscle mass and the exertable muscle force a patient has when getting ill plays a big part. Also the decrease in muscle contraction force related to aging leads to weakness that can exceed what would be expected in the presence of muscle atrophy [Batt J, 2013]. Other studies have reported that gender is associated to ICUAW, with the female gender being a risk factor for ICUAW [L. J. De Jonghe B, 2002]. From these known risk factors some can be influenced or modified, while for others there is no way to clinically control them. Hyperglycemia and sedative medications can be controlled and influenced by doctors, while age, gender, organ failure, sepsis and the requirement for some medication or treatment can not be altered [H. J. Schweikert W, 2007].

From [Table 1] we can conclude that after one week of ICU admission a significant decrease in muscle strength can be found. This has been shown in the way of grip strength and upper limb strength. Older age seems to be directly linked to weakness, severe respiratory muscle weakness is associated with limb weakness and severe muscle weakness can be directly linked with mortality.

As [Appleton R, 2012] noted, 46% of the patients with severe sepsis, multiple organ failure, or prolonged mechanical ventilation will develop ICUAW. The severe effects of ICUAW are easily recognized as 80% of post-ICU patients can not return to their pre-admission residence after discharge. ICUAW can also be independently linked to hospital mortality, with severe muscle weakness being an indicator. Even though there is no direct independent link between diminished grip strength and hospital mortality, measuring grip strength has shown to be a representative measure to show upper body muscle weakness [Ekstrand E, 2016].

2.1.2 Early mobilisation

Early mobilisation is defined as any activity beyond range of motion that is initiated within the first 2 to 5 days of critical illness and continued during the ICU stay. It considers both the application and intensification of physical therapy and any additional specific mobilisation-enhancing intervention method such as active mobilisation of patients requiring mechanical ventilation and the use of other novel techniques. Long-term studies on patient recovery after critical illness have demonstrated severe and prolonged neuromuscular dysfunction and mental problems related to their prolonged bed rest [Herridge, 2009]. In patients that require mechanical ventilation for more than 7 days the effects seem to be the worst, there is a reported incidence of 25 to 60% for ICU acquired weakness [S. T. De Jonghe B, 2009; "NICE guidelines", n.d.; Saxena MK, 2012]. Research in the effects of early mobilisation show improvements in physical capabilities, mobilisation and an increase in exercise time, but also a decrease in needed assistance can be seen. Next to that multiple researches show that participants that received a form of early mobilisation get out of bed earlier and stay in the ICU for a shorter period of time.

Most recent research finds the same conclusion when it comes to early mobilisation safety and feasibility in the ICU; it deems both safe and feasible and shows great potential for the future [Olkowski BF, 2013]. Many international practice guidelines have been produced on the subject of early mobilisation and it is already a well known practice on the ICU [Cox CE, 2009]. However, it has been shown multiple times that even though the outcomes of early mobilisation studies are so promising, these studies do not always result in improved patient-centered outcomes. One of the reasons may be because randomised trials do not show nearly as much early mobilisation as specified and observational studies report low early mobilisation rates during ICU stay [Jones, 2012; Livingston DH, 2009; Timmers TK, 2011.]

Because of the complexity of and the difference in reasons patients have to spend their time in the ICU, early mobilisation is a lot more complex than in other parts of the hospital. Delicate considerations have to be made and cooperation in a team with varying backgrounds have to be made to ensure patient safety [Van der Schaaf M, 2009]. This is one of the main barriers that results in a lower patient mobilisation than desired. This together with all other barriers can be organised into four different groups; patient-related, clinician-related, protocol-related or ICU contextual-related barriers. Patient safety is the most important and main reported barrier for delivering early mobilisation. Mechanical ventilation, invasive lines or tubes, cardiovascular and neurological stability are the usual patient-related barriers that inhibit early mobilisation, but patient refusal to exercise due to fatigue is another often noted problem [Livingston DH, 2009].

From studies however, it shows that the main concerns that keep nurses from mobilising their patients, do not often actually inflict harm to the patient. The potential safety effects of mobilising are a lot lower than expected. From the 11983 mobilisations reviewed there were 186 safety events, which comes down to 1 in every 64 mobilisations, and from all these 186 events none of them were severe. In most cases just stopping the exercise or returning to bed were a good enough solution to prevent any further harm. This shows that there is an opportunity to safely mobilise patients more often.

Even though the studies reviewed in this paper were focused on looking at the possible safety effects of early mobilisation, some results of the mobilisation have been reported as well. In all of these cases the early mobilisation led to an improvement in patient mobilisation, physical capabilities, increased exercise time and a decrease in assistance needed. No negative side effects in terms of a patient's physical capabilities were noted.

2.1.3 Gaming as rehabilitation

A major concern in rehabilitation is that patients do not reach a sufficient amount of practice to induce neuroplastic adaptations underlying behavioral improvements. This can be either related to the patient input or the healthcare provider, but usually it's a combination. There is a lack in enjoyable rehabilitation solutions that intrinsically motivate the patient to exercise.

As a lot of research has been done on post-stroke rehabilitation where they combine conventional therapy with video games, this was the most widely available source that came close to ICU settings. Besides that, 6 recent studies on interactive gaming on the ICU have been reviewed as well. From the studies done on the ICU we can see that the use of video games in rehabilitation seems safe, patients scored higher in different physical and cognitive tests, patients seemed to enjoy the therapy more than conventional therapy and one study suggested that it may decrease hospitalisation time.

The positive physical effects that interactive video games can offer are well proven from the different post-stroke rehabilitation studies reviewed. From the researches done on the Nintendo Wii, most show significant physical improvements and, where measured, interactive video gaming also seems to have a significant positive effect on perceived QOL, cognitive functioning and mental health [Choi JH, 2014; Simsek TT, 2015; Yatar GI, 2015; Yong Joo L, 2010].

Wii group participants showed a significant improvement in balance [Barcala L, 2013; Lee, 2013; Morone G, 2014; Yatar GI, 2015], grip strength [Choi JH, 2014; Yong Joo L, 2010], functioning in Activities of Daily Living (ADL) [Barcala L, 2013; Choi JH, 2014; Lee, 2013; Simsek TT, 2015; Yatar GI, 2015] and general motor function [Barcala L, 2013; Bower KJ, 2014; Choi JH, 2014; Hijmans JM, 2011; Hung JW, 2015; Mouawad MR, 2011; Saposnik G, 2010]. Besides that general improvements in upper limb function, motivation and cognitive function were mentioned.

For the Playstation studies, all trials found that patients seemed to enjoy the games and that adherence to the therapy was higher than the control groups. However the significant results were limited [Neil A, 2009; Rand D, 2008; Yavuzer G, 2008].
The three studies that used the Xbox kinect system found significant increases in upper limb function, balance and muscle strength [Lee, 2013; Sin H, 2013; Song GB, 2015].

The use of interactive gaming devices in the ICU seems to be rather new and unexplored. All articles found were published between 2010 and 2020, and, after exclusion of studies with under-age participants, only 7 eligible articles remained.
The use of the so called bedside cycle ergometer has been studied for a long time, and is a well known rehabilitation device. It is used both passively and actively to stimulate exercise of the legs in bedridden patients. Coupling it to an interactive video game however, seems to have beneficial effects to patient rehabilitation. Patients using interactive in-bed cycling seemed to score better throughout a range of tests. A higher distance was covered, higher peak resistance measured and they seemed to enjoy the video game therapy more than conventional therapy [Hendriks MMC, 2019]. Another study conducted on video game in-bed cycling on the ICU also shows that the participants had improved physical capabilities compared to the control group and were active for a longer time [Kho ME, 2016].

2.1.4 Discussion

The effect of early mobilisation within the first days of hospitalisation is not well documented, the effects of this combined with interactive video games were not found at all. All studies found on early mobilisation were conducted multiple days after ICU admission, which makes them more rehabilitation studies than actual EM studies. Thus no conclusions can be made whether early mobilisation with video games would affect patient recovery. The problem is however that very early mobilisation on the ICU is often hampered by the exact reason the patient is on the ICU. Their condition is so life threatening that usually all their energy and attention in the first few days should be focused on survival.

All gaming devices used in the reviewed studies were commercially available devices, which were not designed to work for people with physical weaknesses. Participants have indicated frustrations with the inability to properly hold the Nintendo Wii remote. They also struggled with understanding instructions in a foreign language [Yong Joo L, 2010]. Whether commercially available devices are appropriate for rehabilitation purposes in the ICU can not be answered clearly from this review, but shortcomings from these devices are mentioned. Parke [Parke S, 2010] noted that there were technical errors because of interference from patient surroundings with the 3D camera used. Due to all the interfering medical equipment (lines, cables, mechanical ventilation) and surrounding objects (bedding, clothing, furniture) the infrared camera used had trouble registering the patient.

2.1.5 Literature review limitations

There is a big overlap in research articles that cover ICU-acquired weakness and early mobilisation of ICU patients, which leaves little articles that focus solely on one of these aspects.

Searches were done to find articles on motivation of ICU nursing staff, but unfortunately this did not deliver any useful information. It would be interesting to see whether a relation could be found between the lack of exercise on the ICU and the motivation of ICU nursing staff. It might be possible that more enjoyment in getting a patient to exercise increases the motivation of ICU nursing staff, which in turn could lead to more mobilisation.

A lot of the research done on gaming as a form of rehabilitation, especially in ICU setting, is done with underage participants, which were not relevant for this review. This led to a relative low number of papers to review for adult participants in the case of ICU gaming.

Most papers reviewed are not carried out as early into the ICU admission as would be desirable; the effects of early mobilisation within the first days of hospitalisation are not well researched. Kho ME, 2016 is one of the few articles found that shows mobilisation on the first day. This is mostly because patients that are admitted to the ICU are usually in such a bad physical condition, that they are not capable of exercising. This leaves a very small group of patients that are physically strong enough to exercise very soon after admittance to the ICU.

The effects of gaming in post stroke rehabilitation are well studied. The outcomes are usually promising and significant improvements in QOL, ADL, balance, confidence and motor function were found Most papers reviewed were carried out with subjects that were capable of being mobilised. There is very limited research done with ICU patients who are not strong enough to get out of bed. This is mostly because they can not be mobilised as in the definition of the word, but the effects of bed exercise are not extensively researched.

What was already known

- Post intensive care unit syndrome causes major problems in patient recovery after discharge from the ICU.
- Early mobilisation can positively affect patient general body function and recovery time.
- Interactive video games can have a positive effect on patient cognitive functioning, mental health, motor skills and adherence to rehabilitation.

What this literature review adds

- Video games can be a way to stimulate the intrinsic motivation of ICU patients to exercise.
- Physical, emotional and cognitive functioning after ICU can be improved by adding video games into the rehabilitation program.
- The shortcomings of commercially available video games used for rehabilitation are not well documented.
- Patient specific early mobilisation has shown to be a good way to counteract the effects of PICS.

2.1.6 Literature review conclusions

The effects of ICU admission can be detrimental for the patient's entire life, returning to their own home, job or hobbies after ICU stay are often not certainties. A few days in the ICU can lead to months or even years of recovery, with post intensive care syndrome causing major problems in both physical as well as cognitive abilities. ICU care has been focused too little on post-ICU recovery for a very long time.

The effects of early mobilisation on patient recovery seem promising, most studies show increases in exercise time, MRC-SS scores, physical performance and stability. There are little safety related barriers to start patient specific early mobilisation. As the differences in both physical as cognitive functioning between patients on the ICU differ hugely, there is not one universal solution for early mobilisation that works for every patient. However, with a patient specific approach there can be a form of early mobilisation for nearly every patient.

Even though there is limited research done on interactive video gaming as part of rehabilitation in ICU setting, the approach seems to be a promising addition to regular forms of therapy. From the reviewed studies the suggestion was made that commercially available interactive game devices may improve patient physical and cognitive functioning in different parts of rehabilitation. Different studies show that gaming as an addition to the regular rehabilitation improves balance, grip strength, functioning in ADL and general motor function. They also show the motivational benefits of using gaming instead of conventional therapy, as patients seem to enjoy exercising more when it's incorporated in an interactive game, which in term relates to better adherence to the therapy.

As early mobilisation has proven to be a safe method for rehabilitation on the ICU and research has shown that video games in rehabilitation usually do not add any safety concerns, the use of interactive gaming as an addition to conventional therapy in early mobilisation of ICU patients seems to be a promising new form of therapy to explore.

2.2 Knowledge gained on the ICU

The EMC Rotterdam as well as the Gelre hospital Apeldoorn put me in a lucky position where I could spend time on the actual ICU departments of their hospitals. Here I could perform expert interviews with a number of different ICU caretakers, but they also allowed me to spend multiple days with them, showing me how regular working days on the ICU are being handled.

2.2.1 Expert interviews

During the last months interviews have been conducted with ICU staff of the Erasmus MC and the Gelre hospital Apeldoorn. These expert-interviews are conducted with physiotherapists, nursing staff and intensivists. Also interviews with ICU patients are conducted to get a clearer view of what they are experiencing during their time in the ICU. These interviews are performed to find the shortcomings and see the bottlenecks of regular rehabilitation systems. Also these interviews gave the chance to figure out what the ICU staff would like to see in a gaming device.
Appendix 1 & 2 give a clear overview of all the outcomes of the expert interviews, which were all conducted before February 2020. A small recap of knew knowledge and insights is given below.

- Nintendo Wii games have been tried to get patients to play games. Problems were found in the complexity and speed of the required movements and the combination of both pressing/releasing buttons and moving the controller at the same time. Also they found that the games were often too hard to understand and that patients were not capable of holding the controller good enough.
- There was no real interest in complex games that would need a patient to transfer from laying to sitting or sitting to standing. They were looking more into small and simple games.
- A big group of patients is too sedated to move on their own power. A lot of passive physiotherapy is used here. These patients can not play any games.
- Care givers would like to show patients their achievements during their time on the ICU. For instance, “last week you only scored 5 but this week you scored 10”. They say that showing progress stimulates patients.
- One of the biggest wishes from the ICU staff was a system that is so easy to operate that even the patient or the patient’s family could start it up and play with them. They want to lower the threshold for rehabilitation or gaming as much as possible.
- Care givers noted that other shortcomings with current games were that they would not observe very small movements and patients could not reach the required range of motion for the game.

Besides these interviews time has been spent on the ICU with the same group of care-givers in their daily routine to see what the problems are they run in to. The goal of these interviews and experience was to get a better idea of what the real problems are that they see on a daily basis.

2.2.2 Observations from the ICU

Before starting this master thesis, I had the chance to spend some time with the physiotherapists of both the Gelre hospital as well as the EMC. This field study gave me the chance to see the day-to-day routine of physiotherapists, but also to study the problems they encounter. These problems, both patient as well as material related, gave me a better idea of what would be needed to design a device that is actually going to be used on the ICU.
During my thesis, Ben van der Hoven, Intensivist at the EMC, invited me to spend a few days with him during his daily routine on the ICU. This extraordinary opportunity was something I could not pass by, so of course I said yes. This week showed me another side of the ICU and helped me understand better how involving care for critically ill patients actually is. With so many different patients that all need different care from different departments of the hospital, the communication can be a demanding tasks on it's own.
Appendix 1 & 2 show the entire overview of my findings during my time on the ICU. A small recap of all the things I learned from real life experience is given below.

- During my time at the ICU of the EMC Rotterdam I noticed that they took a different approach than the Gelre hospital. The ICU staff in the EMC seemed to prefer a more "hands-on" approach, and tried more things with a patient than I had seen before. They want to get patients out of bed when they can and have them practicing in the rehabilitation room or just generally walking or even sitting up.
- I noted that patients often do not have their required glasses with them. This means that a smaller screen can not be seen good enough to play a game. For the end product a big screen that can be placed close to the patient should be used.
- Patients are often only capable of doing a few repetitions before they loose focus. This is hard as this would mean that after a few seconds in the game it has to be explained again.
- I noticed a lot of trembling in patients when they were asked to, for instance, flex their shoulders or their biceps. This would make it hard if the controller should read angles.
- Current gaming devices in the rehabilitation room of the EMC have problems with recognising patients that are have many lines and tubes on their body. Also the ICU chairs are often too big and hamper the cameras in recognising patients.

3 Define

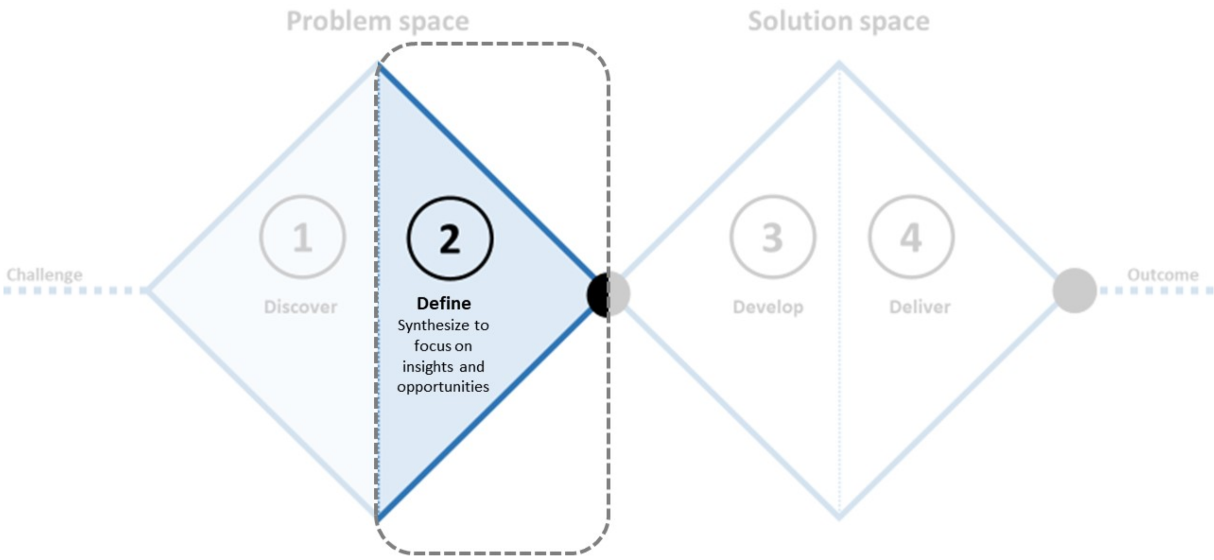


Figure 5: Double diamond design: Define

The define phase will answer the following sub questions:

5. What are the barriers to current rehabilitation techniques?
6. In which ways can ICU patients physical and cognitive functioning be scaled?
7. What is the target audience for which the system will be designed?
8. What are the possible movements that can be used as an input for the game?
9. How is gaming currently utilised for rehabilitation on the ICU?

3.1 Barriers to Rehabilitation

Jolley S.E., 2014 carried out a survey under 120 clinicians in a single ICU in Seattle to study the perceived barriers to early mobilisation. The most frequently reported cross-disciplinary barriers to EM were staffing and time. Nurses indicated a high risk of self-injury and physical therapists reported an excess work stress related to mobilisation.
The main barriers reported by physicians were time taken up by other staff (Nursing, physiotherapists and respiratory therapists), sedation, delirium and patient safety. Figure 6 shows the results of the physicians' survey. The bars represent the percentage of physicians who noted this specific part as a barrier to early mobilisation.

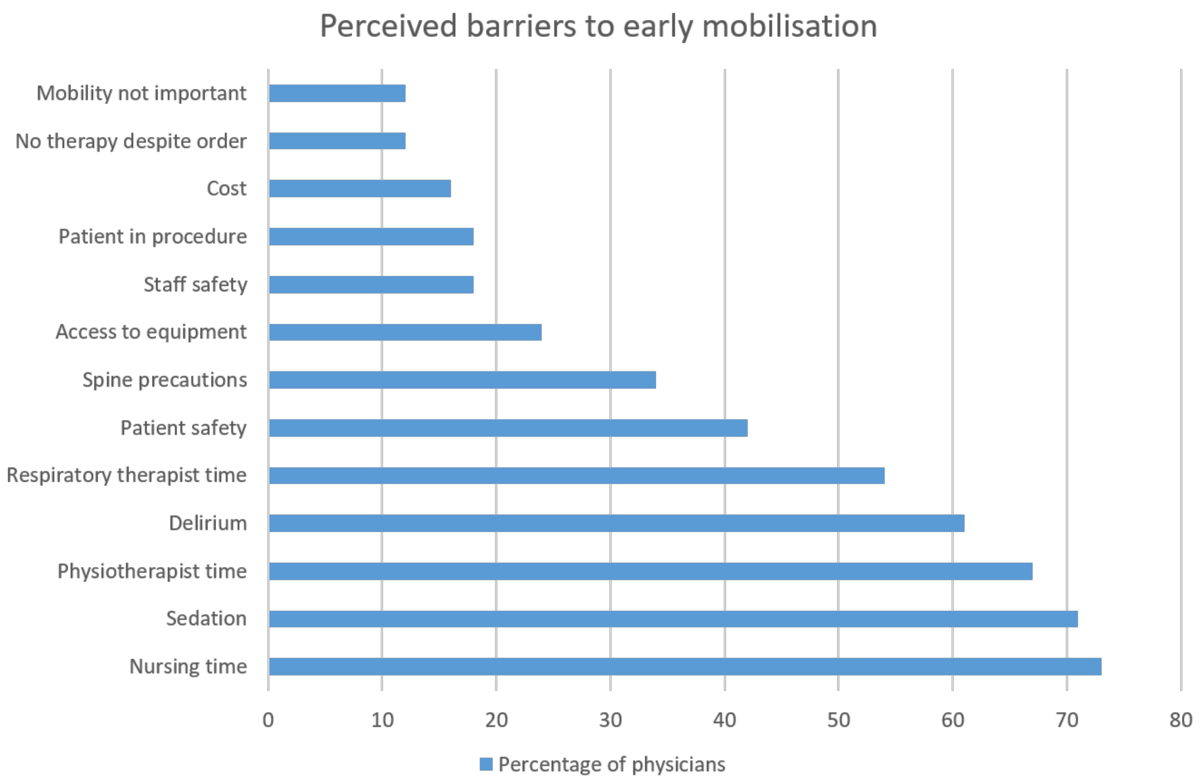


Figure 6: Barriers to rehabilitation

To increase the time spent on rehabilitation, it would be best if we could change the perceived barriers from figure 6. However, this is for the biggest part impossible. We can however aim to make a device that is usable for a large audience. By designing the system in such a way that nursing staff or the patient's family can help start it up to exercise with the patient, the threshold for exercise can be lowered.
Another proven benefit of involving a patient's family in rehabilitation is that the family feels more in control of what is happening. This may help the family members with their PICS-F, but it can also help the patient as more contact with family members helps reduce and prevent delirium.

3.2 Apache II score

The Acute Physiology and Chronic Health Enquiry (Apache-II) score, is a severity of disease classification system that uses a point score based upon initial values of 12 routine physiologic measurements [Knaus WA, 1985]. These measurements are: body temperature, arterial pressure, heart rate, respiratory rate, oxygenation level, several blood values and the Glascow coma score (GCS). For each of these measurements a score between 0 and 4 is added, and the sum of all the 12 scores accounts for part of the APACHE-II score. The other part of the APACHE-II score is made up out of a score given for chronic health issues and age. The total score can range anywhere between 0 and 71. Figure 7 shows the way the scores are distributed for each measurement.

	Physiologic variable[b]	Point score								
		+4	+3	+2	+1	0	+1	+2	+3	+4
1	Temperature	≥41°	39–40.9°	–	38.5–38.9°	36–38.4°	34–35.9°	32–33.9°	30–31.9°	≤29.9°
2	Mean arterial pressure (mm Hg)	≥160	130–159	110–129	–	70–109	–	50–69	–	≤49
3	Heart rate	≥180	140–179	110–139	–	70-109	–	55–69	40–54	≤39
4	Respiratory rate(non-ventilated or ventilated)	≥50	35–49	–	25–34	12–24	10–11	6-9	–	≤5
5	Oxygenation:									
	a) $FiO_2 \geqslant 0.5$: use $A\text{-}aDO_2$	≥500	350–499	200–349	–	<200	–	–	–	–
	b) $FiO_2 < 0.5$: use PaO_2 (mm Hg)	–	–	–	–	>70	61–70	–	55–60	<55
6	Arterial pH	≥7.7	7.6–7.69	–	7.5–7.59	7.33–7.49	–	7.25–7.32	7.15–7.24	<7.15
7	Serum Na (mMol/L)	≥180	160–179	155–159	150–154	130–149	–	120–129	111–119	≤110
8	Serum K (mMol/L)	≥7	6–6.9	–	5.5–5.9	3.5-5.4	3–3.4	2.5–2.9	–	<2.5
9	Serum creatinine (mg/dL): double point score for acute renal failure	≥++++3.5	2–3.4	1.5–1.9	–	0.6–1.4	–	<0.6	–	––
10	Hct (%)	≥60	–	50–59.9	46–49.9	30–45.9	–	20–29.9	–	<20
11	WBC (in l000s)	≥40	–	20–39.9	15–19.9	3–14.9	–	1–2.9	–	<1
12	Glasgow coma score (GCS)	Score = 15 minus actual GCS								
Acute physiology score is the sum of the 12 individual variable points										
Add 0 points for the age <44.2 points. 45–54 years: three points. 55–64 years: five points. 65–74 years: six points≥75 years										
APACHE II score = acute physiology score + age points + chronic health points. Minimum score = 0; maximum score = 71. Increasing score is associated with increasinf = g risk of hospital death										
Add chronic health ststus points: two points if elective postoperative patient with immunocompromise or history of severe organ insufficiency: five points for nonoperative patient or emergency postperative patient with immunocompromise or severe organ insufficiency[c]										
13[d]	Serum HCO_3(venous-mMol/L) use only if no ABGs52	≥52	41–51.9	–	32–40.9	22–31.9	–	18–21.9	15–17.9	<15

Adapted from Knaus WA. Draper EA. Wagner DP. Zimmermam JB: APACHE II: A severity of disease classification system. *Critial care medicine* 13: 818–829. 1985.
Interpretation of APACHE II scores (predicted mortality rate).
0–4 = ∼4% death rate 10–14 = ∼15% death rate 20–24 = ∼40% death rate 30–34 = ∼75% death rate.
5–9 = ∼8% death rate 15–19 = ∼25% death rate 25–29 = ∼55% death rate Over 34 = ∼85% death rate.

[a] APACHE II Score = acute physiology score + age points + chronic health points. Minimum score = 0; maximum score = 71. Increasing score is associated with increasing risk of hospital death.

[b] Choose worst value in the past 24 h.

[c] Chronic health status: Organ sufficiency (e.g. hepatic, cardiovascular, renal, pulmonary) or immuno-compromised state must have preceded current admission.

[d] Optional variable: use only if no ABGs.

Figure 7: Apache II scoring system

The Apache-II score is the most used tool for analysing a patient's illness severity, but it has also shown to be a reliable estimation for ICU mortality. It has been developed in a general ICU and may not be the most precise when tested in a more specific patient groups like the cardiac ICU or for, for instance, HIV patients. The Apache-II score can only be used for patients newly admitted to the ICU, when a patient is transferred from another part of the hospital this method may not be accurate.
The Apache-II score is used by a big part of the care-giving staff on the ICU. A high Apache-II score can be one of the contraindications for rehabilitation and mobilisation.

3.3 MRC scale

The Medical Research Council scale is a way of measuring a patient's muscle force [P. M. Schweikert W, 2009]. The total physical strength of ICU patients is often scaled with the medical research council sum-score (MRC-SS), which is a summation of the MRC scores for different body parts. For the measurement of the MRC-SS 6 different movements are considered for each side of the body. This comes down to a total of 12 measurements, which can range from a minimum of 0 and maximum of 5 points for each measurement. The total summed score for all measurements is then anywhere between 0 to 60 points. A summed score below 48/60 is an indication for ICUAW or significant weakness (unless otherwise specified criteria, for instance from a severe trauma, are present), and an MRC score below 36/48 indicates severe weakness.

The list below shows each of the 6 movements that are used for measuring the MRC-SS

- Evaluated muscle movement[Hermans G, 2015]
  - Wrist extension
  - Elbow flexion
  - Shoulder abduction
  - Ankle dorsiflexion
  - Knee extension
  - Hip flexion

For the rest of this study we will use the term MRC score and not MRC-SS. We will only focus on the MRC score of the muscles involved in the to be decided movements. The total MRC-SS score might give a distorted image for patients that can not yet be mobilised but have decent strength in their upper body.

The list below shows which MRC score relates to what kind of muscle force:

- MRC scale [P. M. Schweikert W, 2009]
  0. No muscle contractions
  1. Flicker of movement
  2. Movement with gravity eliminated
  3. Movement against gravity without resistance
  4. Moderate movement against resistance
  5. Normal power

Sometimes, to give a more specific scale for the MRC score of a single joint/muscle group, there are two extra obtainable scores added around the 4 mark. These extra points are 4- and 4+ and are meant to give a better understanding of what moderate movement actually means; 4- is defined as slight movement against resistance and 4+ is defined as sub-maximal movement against resistance. Often there is more context needed than the regular MRC scale can give, when for instance the patient has enough force to do some exercises with a little extra resistance, but is not strong enough to be considered a MRC4. This could be an indication for an MRC4- score instead.

3.4 RASS scale

The Richmond Agitation-Sedation Scale (RASS) is a validated method to assess patients' agitation sedation level in the ICU [Sessler NC, 2002]. It puts out a score between -5 and +4 to help the caregiver to alter the prescribed sedatives with the goal to end up with a RASS of -2 to 0. Sometimes there is a deviation from the desired score, for instance when a patient meets the indication for deep sedation because of for instance illness severity. A RASS of -2 to 0 is desired and has shown to reduce mortality, to decrease the duration of mechanical ventilation and to reduce the length of stay in the ICU.

- RASS scale
  - +4 Combative
  - +3 Very agitated
  - +2 Agitated
  - +1 Restless
  - 0 Alert and calm
  - -1 Drowsy
  - -2 Light sedation
  - -3 Moderate sedation
  - -4 Deep sedation
  - -5 Unarousable sedation

3.5 Patient physical functioning

As there are so many different reasons patients need critical care, and the differences even between patients with similar reasons for admission are huge, there is no way to make a seperate group of patients for every possible combination of physical, mental and cognitive scores. For this reason a differentiation between three different groups has been made, with a different sub-group for MRC-SS scores within these groups. The differentiation has been done on the mobility of the patient, which gives us; the group that is immobile and can not leave the bed, the group that is partially mobile and (with help) could be transferred to a special ICU chair and the last is the group that is mobile enough to sit upright on their own power and is able to leave the bed.

3.5.1 Immobile

Immobile patients are -in this paper- defined as patients that can not leave their bed under their own power nor with the support of their caregivers. These patients are subjected to rehabilitation supported by physical therapists, but more often than that this is the patient group that is incapable of exercising at all. Usually physical therapists apply passive rehabilitation methods to make sure the joints of this group stay mobile. This patient group would usually have an MRC score of 3 or lower.

3.5.2 Semi mobile

Semi mobile patients are -in this paper- defined as the patient group that is capable of being mobilised with the help and support of their caregivers. They are strong enough to somewhat stabilise themselves when seated but not strong enough to support their own body weight while standing. This patient group is capable enough to do some light exercises against gravity and with some resistance added to the movements. This patient group would usually have an MRC score ranging from 4- to 4+.

3.5.3 Fully mobile

Fully mobile patients are -in this paper- defined as the patient group that is capable of being fully mobilised. This is the patient group that is capable of sitting on the edge of the bed by themselves and stabilising their own body, but can sometimes also be mobilised out of bed to do rehabilitation exercises in the practice rooms. This patient group scores an MRC score of 5, which is almost the maximum achievable score.

3.6 Patient cognitive functioning

Similar differences to those visible in the physical functioning of ICU patients, can be seen between the cognitive abilities of different patients. To distinguish these groups of patients a bit more clearly, three different subgroups have been made. The considerations have been made on how cooperative a patient is. Uncooperative patients are fully non-responsive, semi cooperative patients respond to part of the questions asked but are able of generating contact with their caregivers and fully cooperative patients can make contact and answer to questions the caregiver might ask.
The S5Q score gives a useful indication of the level of cooperation of a patient:

3.6.1 S5Q Score

The S5Q score is a standardised series of questions to determine the patient's level of cooperation [Sommers J, 2013]. The questions are:

1. Open and close your eyes
2. Look at me
3. Open your mouth and stick your tongue out
4. Nod yes and shake no
5. I will count to 5, afterwards frown your eyebrows.

For every action fulfilled correctly one point is appointed. 5 points are appointed at full cooperation.

- Score < 2: Non cooperative
- $2 \geq$ Score ≤ 4 : Moderately cooperative
- Score > 4: Fully cooperative

3.6.2 Non cooperative

Non cooperative patients are -in this paper- defined as the patient group that is fully sedated or asleep. These patients can be in a comatose state for one of many reasons, or can have a hypoactive delirium, which leads them to be non responsive when contact is trying to be made. [Boettger S, 2011]

3.6.3 Semi cooperative

Semi cooperative patients are -in this paper- defined as the patient group that is conscious and capable of generating contact with caregivers when desired. These patients are capable of performing simple tasks but will often loose focus after just a few repetitions. These patients are not able of having conversations but can sometimes answer to simple questions asked.

3.6.4 Fully cooperative

Fully cooperative patients are -in this paper- defined as the patient group that is fully conscious and capable of generating full contact with the environment. These patients can understand more difficult tasks and are capable of doing multiple tasks in a row without losing concentration. These patients are at least able of having short conversations with their caregivers.

3.6.5 Delirium

One of the reasons patients on the ICU might not be fully cooperative is Delirium. Delirium is defined in the American Psychiatric Association's (APA) Diagnostic and Statistical Manual of Mental disorders (DSM)-V as a disturbance in consciousness and cognition that develops over a short period of time (hours to days) and fluctuates over time. Delirium is a often seen form of acute brain dysfunction in critically ill patients and is associated with increased risk of morbidity and mortality. [Shu-Min L, 2004]

3.7 Current rehabilitation methods

Whether or not an ICU patient will be actively mobilised will be judged by the care-giving physiotherapist and physician. For this a good assessment of the patient's condition has to be established, which includes APACHE-II, MRC-SS, RASS and S5Q score. These scores on their own often do not give a full representation of the patient, but an individual aberrant score may still be an contraindication for early mobilisation. From these combined scores a good representation of the patient's abilities can be made, which is necessary for any further mobilisation or rehabilitation purposes.
The physiotherapists of the EMC do not use any pre-generated protocols for the physical therapy of the ICU patients. There are protocols made for ICU mobilisation, but from conversations with the physiotherapists it became clear that these protocols do not account for the entire spectrum of patients. The variety in both physical as well as cognitive functioning of the ICU patients is just too big to be captured in a protocol.
An easy to use checklist before active rehabilitation is the red flag list. Most of these red flags are based on health issues that would be dangerous for anyone; extremely high or low blood pressure or heart rate, fever, low body temperature and other physical abnormalities. Appendix 8 shows all the criteria considered to be contraindications for mobilisation and active rehabilitation [Sommers J, 2013]. When either one of these red flags is present, rehabilitation can not be started as the safety risks of the patients outweigh the possible benefits rehabilitation might have at that point.

3.7.1 Non responsive patient

Non responsive patients can not be actively mobilised as voluntary muscle contractions are not possible for this patient group. Because of this, non responsive ICU patient will only receive passive forms of therapy. Passive exercises or passive range of motion exercises, are exercises in which patients do not use their own muscle force to move through their range of motion. Instead the physical therapists passively moves their limbs to flex and stretch their limbs, so that the muscles stay activated and flexible. Passive range of motion exercises have the following main goals:

- The prevention and reduction of edema
- The prevention of involuntary muscle contractions and tonus regulation
- The increase in the range of motion. For this stretching and Continuous Passive Motion (CPM) are needed.
- To improve muscle force and to prevent muscle atrophy

Passive in-bed-cycling is an often executed passive range of motion exercise, figure 8 shows a commonly used setup. In the active version of this exercise the patient uses their own muscle force to make a cycling movement on an ergometer. In the passive version however, the patient's feet are attached to the cycling machine, which starts rotating slowly, making the patient's legs move in the cycling motion. The use of passive cycling has shown to improve the functional status of the patient [Machado dos Santos A, 2017].

3.7.2 Responsive patient

For responsive patients the physical therapists are, depending on the MRC-SS, usually not bound to only passive exercises. However when patients have a very low MRC-SS it can still be possible that the patient can only receive passive rehabilitation.
Depending on the physical functioning of the patient, specific active exercises may be possible. The range in different exercises is also entirely related to the patient's physical functioning. Different MRC scores for different body parts can provide an indication of what exercises are possible. This can range from exercises as small as only muscle contractions to mobilisation out of bed. Section 3.9 gives an indication of the most commonly used upper- and lower body exercises for ICU patients.

3.8 Target audience

As the scope of this study is focused on testing the feasibility of interactive gaming on the ICU, the goal is not designing a system that is usable for all ICU patients. Instead, a target audience has been selected based on a variety of parameters for inclusion, to assess the feasibility of the final design. The feasibility tests of the final design will be tested on the general ICU of the EMC Rotterdam, which already limits our target group to adult subjects. Besides that, we tried to select a target audience that does not narrow down the number of subjects too much, but still only includes subjects that are capable of understanding and playing the game. Therefor the following requirements for the target audience have been decided:

The participant should be able to perform easy tasks and should be able to respond to the game. In order for the participant to successfully play the game, the participant should understand that their input delivers a certain output on the screen. The feedback on the screen should be translated into a different movement to ensure the game is played correctly. Basically the participant should understand that he or she is controlling the game. For this the patient should be awake and cooperative, have at least basic muscle functioning and should not be considered to have any counter indications for rehabilitation, that would usually exclude them for rehabilitation exercises.

Given the cognitive and physical requirements of the patients to successfully play the game, the following limitations have been set for the target audience:

- Only adult patients
- MRC score of 4- or higher
- RASS scale between -2 and 1
- S5Q score of 5
- Patient is at least semi mobile
- Patient is at least semi cooperative
- No red flags for rehabilitation

3.9 Movement analysis

To find the exercises we want to use as the input for our design, we should first establish a list -specified for our target audience- of all the exercises and motions usually performed during physiotherapy. For the selected target audience this can be all movements that the physical therapists could ask the patient to do from their bed or from a chair.

Upper body movements

- Flexion and extension of elbow joints
- Flexion and etension of the shoulder joints
- Abduction and adduction of the arms
- Circumduction of the wrists
- Flexion and extension of the wrists
- Flexion and extension of the fingers
- Flexion and extension of the neck
- Rotation of the neck

Lower body movements

- Flexion and extension of knee joints
- Flexion and extension of the hip joints
- Plantar flexion and dorsiflexion of ankles
- Inversion and eversion of ankles
- Abduction and adduction of the hips
- Medial and lateral rotation of ankles

Movements desired by physiotherapists

Interviews with the physiotherapists of the EMC Rotterdam led to a new list with movements they perceive to be the most useful and which they would like to see as the input for a game. This list contains the movements commonly used for ICU patients. These movements are meant to reduce muscle stiffness, increase range of motion, improve general flexibility, increase muscle strength and reduce chances of ICUAW. Another desired outcome of the rehabilitation exercises is to improve the quality of life and to help in activities of daily living, so that patients can live as independent as possible after hospital discharge.

- Flexion and extension of elbows and shoulders
- Flexion and extension of the knee joints
- Plantar flexion, dorsiflexion, inversion and eversion of ankles
- Medial and lateral rotation of ankles
- Flexion and extension of the fingers
- Practice in ADL; lifting and grabbing common objects
- Practicing grip force control

3.10 Current gaming devices

The physiotherapists of the EMC have multiple resources that add some sort of gaming element to the therapy. There is an entire physiotherapy practice room for patients where the patients that are strong enough to be mobilised can be brought to practice. The group we are looking at in this study however, is not strong enough to leave their bed so they can not enjoy rehabilitation games in the practice room. For bed-ridden patients they have a few other devices that are being used. An often used device is the bed-cycle (see figure 8), which can be connected to an ergometer which tracks the patient's performance. This ergometer can then again be connected to a game which is projected on a video screen. In this game the patient can cycle through different projected regions, for instance their own hometown, big cities around the world or even the grand canyon. Patients seem to enjoy this form of therapy and score higher on performance and stamina than patients that use the bed cycle without this game connected [Kho ME, 2016].

Figure 8: In bed cycling ICU patients

Currently they do not use any other forms of video gaming readily available on the ICU rooms. They do give patients stress-balls and other small devices to play with, but these do not offer any kind of feedback. In the past there have been a few extraordinary cases of ICU patients that have had a gaming device on their room. One of these was a younger patient that had to stay in the ICU for a donor. This was not a regular patient and in many ways not comparable to the usual ICU patient. As he was only a teenager he quickly got bored in the ICU environment and for this reason he was allowed to have a Sony Playstation in his room. The device was connected to a set of Virtual Reality (VR) glasses enabling him to play video games while laying in bed.

3.11 Specific design challenge

From the knowledge gained in the "Discover" section and specifying the target audience and all movements that they could perform from without being mobilised, a new, more specific, design challenge has been formulated.

The goal is to create an interactive video game controlling system that allows ICU patients, that are at least semi mobile and semi cooperative, to play video games that simultaneously help in rehabilitation, deliver distraction from the daily routine in the ICU and stimulate them cognitively. This all with the aim to help the patient to leave the ICU in the best physical and cognitive state as possible, so they experience the least trouble in their ADL.

4 Develop

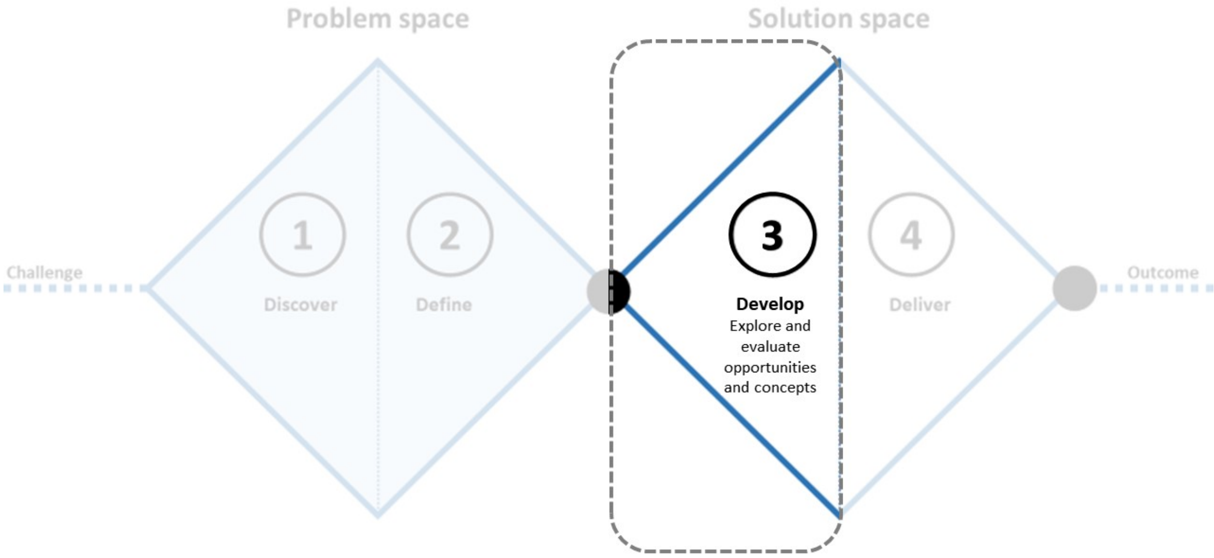


Figure 9: Double diamond design: Design

The develop phase will answer the following sub questions:

10. What are the design goals for a new way of controlling video games for ICU patients?
11. What exercises should be used as input?
12. Which system solutions can be defined to translate this input to the game?
13. What are the essential requirements that should be present in the final solutions?
14. What game solutions can be used for the chosen input form?

4.1 Design goals

The development of a new interactive video gaming device will be focused on user experience design. In our case the user is the ICU patient with characteristics defined in section 3.8. The design is supposed to, first and foremost, help the patient in their rehabilitation. Next to that the game is supposed to also bring the patient some enjoyment and distraction from their stressful and uncertain time during their ICU stay. Keeping patients minds occupied has been proven to prevent delirium, which in turn helps prevent a whole series of other complications and risks [M.J. Strijbos, 2013, Shu-Min L, 2004].

Adding a beneficial factor that can help patients leave the ICU in a better physical and cognitive state and helping them to return to a regular life as soon as possible is eventually what we want to achieve with the design of the system.

The design goals are then: to create an interactive video game system that allows patients on the ICU to play a video game that helps them in preventing and counteracting muscle loss. The aim of this video game is that the patient improves muscle force control, enjoys the game-play and has a form of distraction that helps them to keep their mind of their critical illness for a while.

4.2 Desired movements

As one of the main goals is to have an impact on the patient's ADL and QOL after the ICU, the input used in the design should be a movement frequently used during ADL. In interviews and conversations with the ICU physiotherapists (R. van der Stoep, M.A. Saeijs, A.C.M. Verbiest) of the EMC Rotterdam we discussed the desired training forms that they would like to have integrated in the final design, but also the devices they currently use. From the options provided, we decided to use hand movements as input. These hand movements are commonly used as exercises to train grip force control. To be relevant for ADL, it got clear that they would like to use hand movements that come as close to the functional range of motion of both the MCP as well as the PIP joints as possible. Another desire later discussed with the physiotherapists, was the use of a device that is similar to the stress-balls they currently use, but then incorporated into the game. The problem with these stress-balls currently is that they are non-interactive, and the patients get bored very easily when asked to perform a certain number of repetitions squeezing the ball throughout the day.

Kurillo G, 2005 performed research with a grip force tracking system, in which participants had to play a simple game which they could control by the amount of force exerted on two different devices. The first device required a medium wrap grasp, the other device required a lateral pinch or tip pinch. The task the participant had to fulfill, was continuously tracking the position of a blue ring on a computer screen, by dynamically adapting the grip force to the measuring unit. This way the participant could control the height of the ring while it moved along the screen to make it follow a certain path. The tasks were carried out for 4 weeks with 10 different patients. The results were promising:

"8 out of 10 patients improved the overall accuracy of tracking and consequently achieved better grip force control. Two of the patients (P8 and P10) showed no consistent results of the training with their tracking scores fluctuating between sessions. The patient P8 experienced the last stroke 6 years prior to the testing and also showed no observable improvements in other methods of therapy. The patient P10 was the oldest patient in the group (age 79) which could be a possible factor for a slow progress during the rehabilitation. The patients who were unable to reach the 30% level of their maximal grip strength at the beginning of training improved their performance considerably and were able to reach the highest target levels in the last few training sessions." [Kurillo G, 2005]

This study shows that the effects of grip force training have proven to be successful. This is an extra confirmation for us to use grip force control as our exercise as input for the game.

4.3 Grip strength

The average age of the population keeps rising and a larger part of the population reaches a higher age than before. Elderly people are already the most common patient group on the ICU and the median and average age on the ICUs keeps rising with the aging population [Creagh-Brown B, 2014]. For these reasons there is an increasing need for methods to assist in aging healthy.
The ability to care for yourself for as long as possible is one of the main points related to healthy aging. Being able of living independently and performing ADL are also the main markers that determine the quality of life.

Hand-grip strength is a common way of measuring overall muscle strength and can be used as an indication for health related QOL [Sayer A.A., 2006], the ability to perform ADLs [Hunter J.M., 1995], length of hospitalisation [Roberts H.C., 2012], ICUAW and the prognosis of certain diseases [M.R. Alvares-da-Silva, 2005]. Also, a diminished hand-grip strength can be used as an indication for disability [Bohannon, 2008] and as a predictor for mortality[Ling C.H.Y., 2010] in elderly patients.

Xue-Ping C., 2014 conducted an intervention study with 80 healthy participants; 40 in the intervention group and 40 in the control group. The intervention group did daily exercises for their hand-grip strength, consisting of 10 minutes finger weight-lift training and 20 minutes of finger-movement exercises. Every week the participants' performance was measured during a period of 3 months.
After this 3 month period each individual participant's performance was measured both in ADL ability with the Activities of Daily Living Scale (ADLS) and by their hand-grip strength with a hand dynamometer. (Figure 10a shows the most commonly used hand dynamometer, figure 10b shows another example that uses a spherical grip for measuring hand grip strength.) Hand-grip training and finger movement exercises significantly increased the hand-grip strength of the control group. The control group also noted changes in ADLS scores were noted.
Other studies also showed similar results, Ranganathan V.K., 2001 noted that finger-movement training improves the ability to control submaximal grip force and hand control in elderly participants.
As one of our primary goals for the design is to help patients in their QOL and ADL after ICU discharge, the training of grip-strength is going to be our focus. As during ADL the maximum grip force is very seldom used, the focus will not be on maximum grip strength but instead on improving grip force control in ICU patients.

(a) Hand dynamometer

(b) Spherical hand dynamometer

Figure 10: Two sorts of hand dynamometers

Maximum grip strength

For the optimal operation and the desired effects for rehabilitation, the design should be adapted to the patient's specific physical power. In this case it should be adapted to the maximum exertable grip strength the patient can deliver. ICU patients have a wide variety in their grip strengths, from nearly no exertable force for patients with MRC score of 0-2, up to forces that are equal to that of a healthy person for some MRC5 patients. This means that the maximum exertable force ranges somewhere between 0 and 400+ Newton (N).

Figure 11 shows the average maximum grip force for healthy adults Amaral C.A., 2019. It can be seen that for elderly healthy people the average maximum exertable grip force is somewhere between 21.1 kg and 29.4 kg for male subjects and between 17.1 kg and 23.0 kg for female subjects. However for younger male subjects the maximum can rise up to an average of 38 kg. With a mean deviation of 12.8 this means that it is credible to believe that there are subjects that have scored well over 50kg which corresponds with about 500N.

	Total			Men			Women		
Age (years)	n	Mean	SD	n	Mean	SD	n	Mean	SD
18–29	183	36.2	11.57	46	44.7	10.56	137	28.6	6.29
30–39	136	38.0	12.05	48	46.9	10.39	88	29.4	6.39
40–49	131	35.1	10.05	40	42.7	8.79	91	28.3	5.66
50–59	143	32.7	10.97	50	41.2	8.65	93	24.2	6.06
60–69	415	29.4	9.27	169	36.2	8.15	246	23.0	5.55
70–79	298	25.5	7.95	131	31.3	6.97	167	20.3	5.05
80 and over	156	21.1	6.78	70	25.7	5.81	86	17.1	4.98
Total	**1,462**	**35.2**	**11.55**	**554**	**43.4**	**10.50**	**908**	**27.6**	**6.58**

n = sample size; Mean = mean of the highest HGS value among three measurements of each hand whose upper limb was classified as healthy; SD = Standard Deviation (Estimated by Taylor Series Linearization Method).

Figure 11: Average maximum exertable grip force (in kg)

Unfortunately, there are no similar charts like figure 11 to be found for ICU patients. This can easily be explained as there has been no need for an average grip strength among ICU patients. Each case is different and an averaged or median value would have very little added value.

The physiotherapists of the EMC Rotterdam do however perform measurements with a hand dynamometer (figure 10a) on ICU patients. Their measurements show an expected variety of grip strength that is proportional to the patient's MRC score. The values range from 0 to 300N, depending on, among other things, age, sex, illness severity and sedatives. A score of 0 would correspond to a MRC score of 0 or 1. A score of anything above 50N corresponds to an MRC score of 4 or higher, depending on age and sex.

4.4 Activities of Daily Living

Activities of Daily Living is a term to describe all fundamental skills that are required for a person to independently take care for oneself. It includes all things one may do on a daily basis related to eating, bathing, leisure activities or mobility. The term activities of daily living was first used in an article by Shelkey M., 1999 in 1950. She made a differentiation in ADL and Instrumental Activities of Daily Living (IADL). Because this structure was not sufficient in distinguishing different types of ADLs, Dollar, 2014 proposed to introduce a new sub-classification system of ADLs, designed with different subcategories to show a better difference in what is considered to be ADLs. Appendix 4 shows the different categories.
What can be observed in Appendix 4, is that hands are used for nearly every daily activity. Being able of managing most ADLs without needed assistance helps patients feel more independent. A lacking ability to brush your own teeth, pick up your own glass or spoon, or comb your own hair makes people feel very subsidiary.

The physical self maintenance category can probably be considered the most important category for most people. These are the basic requirements for daily living for most elderly who get some sort of help or support in their household. The domestic activities of daily living make their daily routine a lot easier, being able of preparing your own food and handling your own housekeeping can be enough for basic living for most people. Extradomestic activities of daily living complete the categories and include all regular activities outside one's own household. Being able of handling all these categories on your own is the basic requirement for living completely independent.

4.5 Range of motion

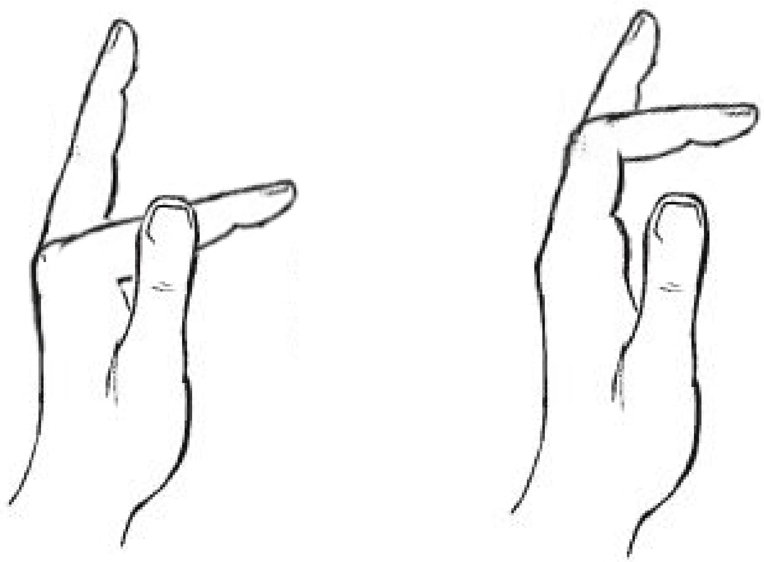
For the ability to control most ADLs, it is important for the hand joints be able to work through the entire functional Range Of Motion (ROM). The functional ROM is defined as the range required to perform at least 90% of the daily activities, utilizing the grasp and pre-grasp measurements [Bain G.I., 2014]. This means that to achieve at least 90% of the ADLs there is a specified minimum angle that has to be reached and a specified maximum angle that has to be reached. For our grasps the specific angles that we will be looking at are the angles of the MCP and PIP joints.

Figure 12 shows the minimum and maximum angles in the range of motion for the MCP, PIP and DIP joints, for both the active ROM as well as the functional ROM. The active range of motion is the range of motion a person can achieve naturally on their own power. The functional range of motion is the range of motion needed for 90% of ADLs.

Joint	Active		Functional (90%)		
	Extension	Flexion	Minimum	Maximum	%Active ROM
MCP all	−19 (SD 6.9)	90 (SD 9.1)	19 (SD 12.2)	71 (SD 8.1)	48
PIP all	− 7 (SD 3.7)	101 (SD 8.3)	23 (SD 8.7)	87 (SD 6.5)	59
DIP all	− 6 (SD 4.1)	84 (SD 8.5)	10 (SD 7.9)	64 (SD 8.1)	60

Figure 12: Range of motion of hand joints [Bain G.I., 2014]

The data from figure 12 shows us that, in order to fulfill the functional range of motion requirements, an MCP angle rotation from 19 to 71 degrees is needed and a PIP angle rotation from 23 to 87 degrees. These rotations can be seen in figure 13a and 13b. These figures show the functional range of motion of the MCP and PIP joints respectively. The fingers are displayed both the minimum as well as the maximum angle for each of the joints. The ideal solution for the final design would utilize a mechanism that works throughout this entire functional range of motion.



(a) MCP range of motion

(b) PIP range of motion

Figure 13: Range of motion for MCP and PIP joints

4.6 Grasp taxonomy

There are many different ways you can use your hands to hold or grab something. Some of these grasps look very similar to each other, others differ completely. They can be arranged in different ways; by the placement of the thumb, the way the palm of your hand is formed, the shape of the device that is being held, the force or the precision needed.
Each grasp has a different specific use, that is why some grasp forms are used very rarely and others are used very frequently throughout the day. The most used version of an overview for grasp taxonomy is made by Feix, 2011. He has organised grasp types by power, precision and made sub-categories for thumb position and finger/palm contact type. His work has identified 33 different grasp which can be seen in figure 14.

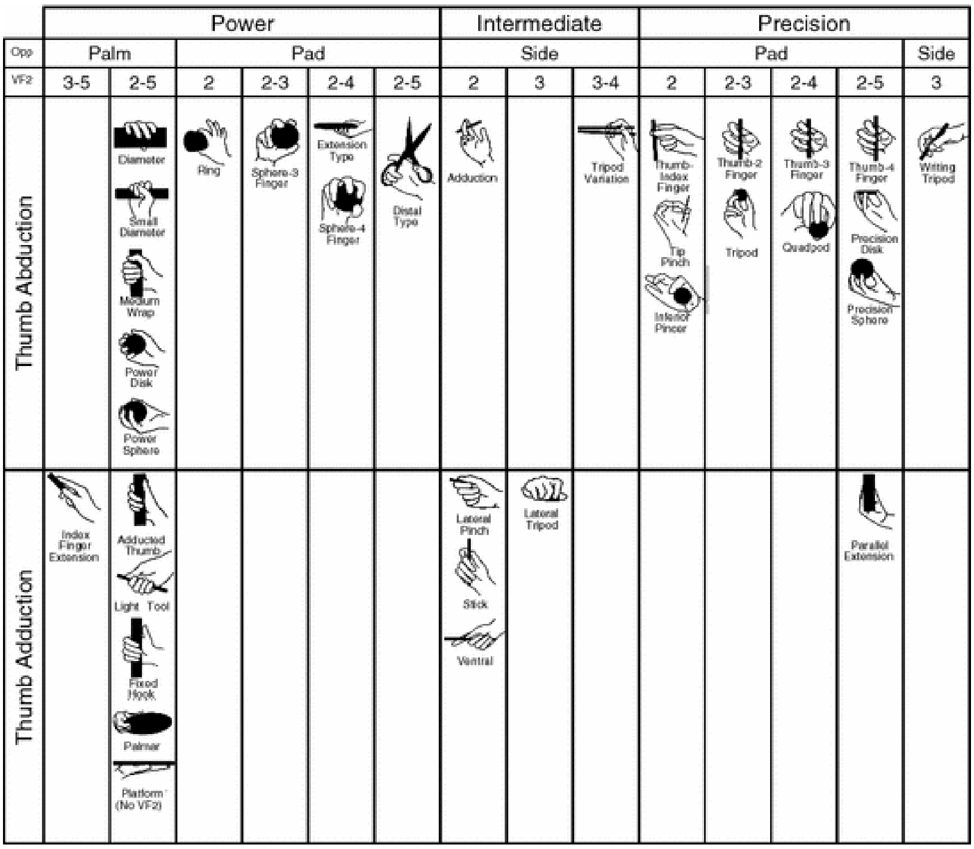


Figure 14: Grasp taxonomy Feix, 2011

To design a device that has influence on the QOL and increasing the physical performance during ADL, we should study what the most commonly For this reason it should be known what grasp types are used throughout the day in ADL. Dollar, 2014 has studied the number of times each grasp has been used throughout the day for both a house maid and a machinist. The frequency data can be seen in figure 15. For people rehabilitating from a critical illness, the "house maid grasp frequency" is going to be considered, as this resembles the day to day activities of a person within their own home the closest.

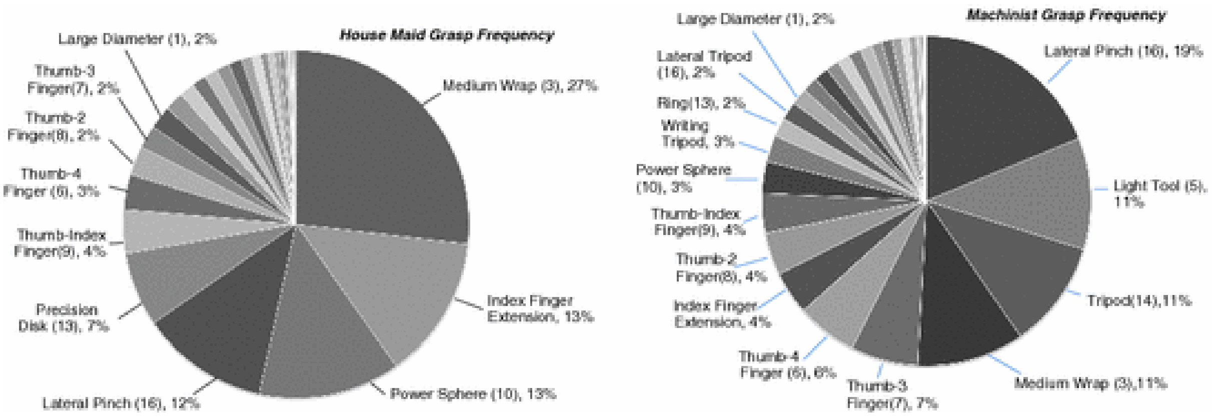


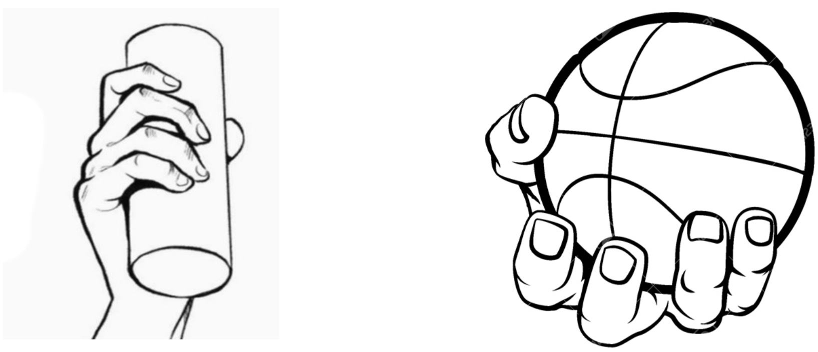
Figure 15: Grasp frequency Dollar, 2014

Figure 15 shows the frequency in which different grasps are used throughout the day for a house maid and a machinist. It shows that the "medium wrap", the "index finger extension", the "power-sphere" and the "lateral pinch" are the most used grasps for the house maid throughout the day.

Bullock I.M., 2013 Has done a similar study to that of Dollar, 2014. In this case the grasp frequency of two house maids and two machinists were studied. None of the subjects had any history with injury or disability that could affect grasping or might manipulate the behavior. Figure 42, visible in Appendix 5, shows the frequency of each different grasp category for all 4 subjects.

In both the studies from Bullock I.M., 2013 as well as Dollar, 2014 the house maids used the medium wrap grasp the most frequently. Consequently, during most of the in figure 42 considered different subcategories for ADL the medium wrap is the most used grasp category. For this reason one might consider the medium wrap to be the most important grasp category for ADL, followed by the power-sphere, precision disk and the index finger extension.
Before deciding on what grasps we should base our final designs, we discussed the outcomes of the studies from Bullock I.M., 2013 and Dollar, 2014 with the physiotherapists of the EMC Rotterdam. As they are the experts that have to be using the device, their ideas should be considered as well. From these conversations we learned that they would prefer to see more power type grasps than precision graps. Also they would not prefer to use any grasps that rely on finger extension.

For the final concepts we therefor made the decision to use the medium wrap (figure 16a) and the power-sphere (figure 16b). This means that we will be focussing more on full hand performance and less on the precision control of separate fingers that would be needed in, for example, the "index finger extension" grasp.



(a) Medium wrap (b) power-sphere

Figure 16: Grasps used for final models

4.7 Ergonomics

Because of the differences between different ICU patients, it is hard to design a device that will always be ergonomically perfect for everyone. But the idea is however, to design a device that is usable for a wide variety of ICU patients. Whether they are short or tall, men or women and have big or small hands, they all should be able to successfully use the device. For this reason it is important to study hand ergonomics before creating the final design. For the purpose of this research, which is about testing the feasibility, we will create the device so it should be ergonomically perfect for the 50^{th} percentile of patients. This means that for the majority of patients it should be ergonomically perfect, but, more importantly, it should still be usable for most other patients on the ICU. Also for the final version we will try to design the device in such a way that adaptation to different hand sizes is easily possible.
The most important dimension that limits people of using the device, is the distance between the intermediate phalanges and the carpals of the hand. This is the dimension that limits the maximum size of the device and so, for testing, we will here use the dimension of the 50^{th} percentile of patients.

4.8 Disposable design

One of the big threats in a hospital's ICU is environmental bacterial contamination. Inanimate surfaces and equipment may easily be contaminated by bacteria and can in this way play a role in cross-contamination of pathogens that can lead to patient colonisation or infection. As critically ill patients are a multiple risk factor group for infection of pathogens, extra caution in handling equipment and surroundings around the patient is needed. Contamination of inanimate surfaces can occur as a result of patient touch, or via the healthcare worker. As Wilson APR, 2011 found in a randomized cross-over study; within 4 hours after cleaning a high touch surface on the ICU with standard cleaning measures, recontamination of the surface occurs again. Standard cleaning procedures may not be sufficient to successfully clean objects that are being used by multiple patients. For this reason, as a design consideration it might be best to design with a disposable design in mind. Reducing the chances of cross-contamination may save lives, that is why for the final design a disposable system, at least for the parts that may contact the patient, is the best solution to minimise chances of patient-to-patient contamination. This way we can use a different device for each different patient, which means two patients will never be touching the same device.

4.9 Concept costs

Tan S.S., 2012 performed a study on ICU costs on ICU departments of hospitals in 4 different European countries, of which the EMC was one. The average cost -in 2006- for one day of ICU stay in the EMC turned out to be 1190€. If you only take account for the inflation, this would equal around 1520€ per patient per day in the ICU in 2020. Because of factors like the aging demography and technical advancements, this cost will likely be even higher today. When taken into consideration that the design should be -at least for the most part- disposable, cost is an even bigger factor to keep in mind. We want to create a threshold for the caregivers that is as low as possible, an expensive design might increase the threshold to start with the game. The final design should be cheap enough that the costs may never be a barrier for the caregiver to use the device for a certain patient.
Each patient will have their own training devices that will be discarded after their ICU or hospital discharge. This is because the design has to be disposable (as discussed in 4.8) to minimize chances of patient-to-patient contamination. It is also an extra reason for the final design to be as cost effective as possible.

4.10 Controlling mechanism

To create the desired input for the game, a sensor has to be used that can translate the force and movement of the patient into the desired output in the game. To choose the appropriate sensor, we should first choose what we want to measure. The general movement we want to measure is the grasping motion of the hand. This movement can be measured in a number of different ways, some of the measurements that could be useful for the controller are:

- Angle of the MetaCarpoPhalangeal (MCP) joints
- Angle of the Proximal InterPhalangeal (PIP) joints
- Pressure on a device
- Force on a device
- Rotation of a device
- Perpendicular translation inside a device

For each of the measurements possible, there are numerous ways to register them. The use of cameras to register movements has been deliberately left out of the comparison as the use of cameras to track motions of people is quite awkward. People tend to turn their hands in different directions which eventually makes it hard for the camera to track the required movements. Also, for ICU patients there are usually multiple sensors, tubes and lines connected to the arms and hands, which get in the way of the camera and hamper the tracking mechanism. For the specific movement of certain fingers of healthy subjects moving their hands in a surrounding with no obstructions, it would be possible to track them with the use of cameras. For critically ill patients that find it hard to do the specified task, cameras would make the concept unnecessarily complicated.

A list was created that couples the possible measurements to the most commonly used sensors for these measurements. The complete list can be seen in table 3. On the left side of table 3 the possible different measurements we could use for the system have been noted. On the right side we see the sensors most suitable for tracking these measurements for our system. Any possibilities for sensors that are much too big, expensive, complicated, or otherwise unusable for our system are left out of the table.

Angle handjoints	Touchless rotary sensor Potentiometer Rotary magnetic Hall effect sensor
Pressure	Capacative pressure sensor Strain-gauge pressure sensor
Force	Force sensing resistor Load cell Shear beam Compression force transducer
Rotation	Touchless rotary sensor Potentiometer Rotary magnetic Hall effect sensor
Perpendicular translation	Inductive distance sensor Ultrasonic sonar distance sensor

Table 3: Sensor options

The decision on which sensor will be used is based on a couple of things.
First of all patient safety should be guaranteed at all times. Any design choice that might harm the patient in any way, has to be discarded. For this we want to evade putting anything to the patient's skin as much as possible. Stickers that have to be attached to a patient's skin are not usable because they can damage the often fragile skin of the ICU patient. Also, we want to eliminate all solutions that

involve attaching things to a patient's hand or wrist as much as possible. Patients often have multiple lines and tubes running from their lower arms and hands to multiple devices. It is easy to dislodge or damage these lines and contact with the needles connected to the IV lines can cause injuries. We do not want to create any safety risks for the patient with our device, so anything that needs to be attached to the patient's hand or wrist is not an option.
Secondly, we want to keep the costs as low as possible. If possible it would be preferred to create a device that is fully disposable, which would either involve a sensor that is very low cost or a sensor that is more expensive but easily interchangeable from one device to another and can easily be disinfected.
Third, we need sensors that are reliable during their lifespan. System failure is very frustrating for both patient and caregiver and can lead to failing adherence to the game/therapy.
Lastly, the accuracy of the device is important but less so than the other characteristics. As we mostly need the device to transfer a range of 4 values. Start, first floor, second floor and third floor. We do not need the sensor to be so specific that it is able of scanning every exact change in degrees, distance, pressure or force.

To decide what sensor would be the best option, a weighted analysis is done with all the different sensor possibilities. One of the biggest considerations in this analysis was the cost of the sensor. Preferably we want to make the design completely disposable, but other than that we want to give each patient their own pair of controllers during their time in the hospital. From the expert interviews we learned that on the ICU things get lost easily. There are many different care-givers that visit the patients' rooms throughout the day, and things get misplaced or lost easily as communication on peripheral matters is not always the best.
The second important aspect is the ease of use of the sensor. We wanted to build a device that can be created, tested and iterated as soon as possible. Making very complicated devices with unnecessary complicated sensors would not be very helpful. For this reason the focus was put on a sensor that has been tried and tested and could easily be adjusted and incorporated in the device we designed.

WEIGHT	**2**	**3**	**2**	**1**	**3**	
	Reliability	Cost	Size	Accuracy	Ease	Total
TOUCHLESS ROTARY SENSOR	1	1	2	2	1	**14**
POTENTIOMETER	2	2	1	3	2	**21**
HALL SENSOR	3	1	1	2	1	**20**
CAP PRESS SENSOR	3	1	2	3	1	**19**
STRAIN-GAUGE PRESS SENSOR	3	1	2	3	1	**19**
FSR	2	3	3	1	3	**29**
LOAD CELL	3	2	2	3	2	**25**
SHEAR BEAM	3	2	2	3	2	**25**
COMPRESSION TRANSDUCER	2	1	2	2	2	**19**
INDUCTIVE DISTANCE SENSOR	1	2	2	3	1	**18**
ULTRASONIC SONAR DISTANCE SENSOR	1	1	3	1	1	**15**

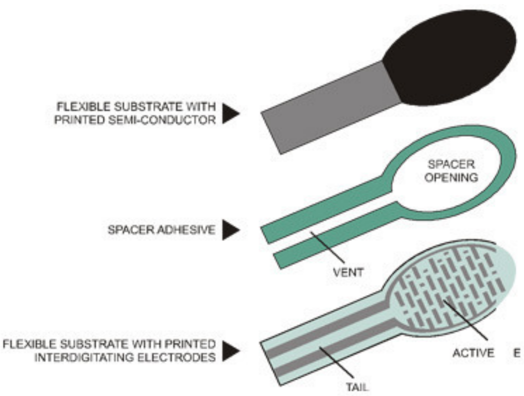
Figure 17: Weighted analysis possible sensors

Figure 17 shows us the weighted table that can be used for choosing between each of the sensors. Each category is given it's own weight based on the perceived importance, with a minimum weight of 1 and a maximum of 3. Each sensor can score on a scale from 1 to 3 for each category, this score is multiplied by the weight and the sum of all these scores is the total score for the sensor.

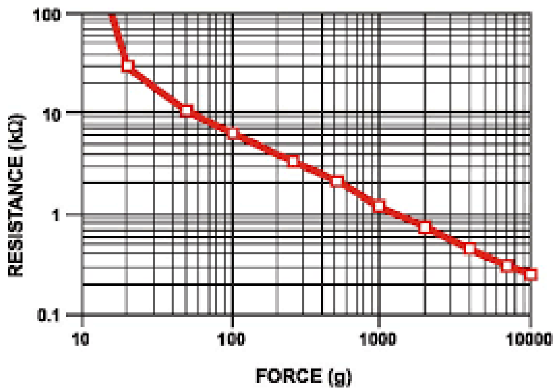
As is visible from figure 17 the FSR, load cell and shear beam score the highest with a respective sum score of 29, 25 and 25 points. The FSR stood out the most as, next to the criteria from the table, it was also by far the smallest sensor. This small size makes it easy to incorporate the sensor in the final design. The problems with load cells and shear beams is that they are usually quite a bit larger than FSRs. They make up for this as they are a lot more accurate than the FSR, but for our purpose the accuracy of the sensor is of less importance.

4.11 Force Sensing Resistor

For the final design the Force Sensing Resistor (FSR) will be used. An FSR is, simply put, a passive element that functions as a variable resistor in an electrical circuit. It dynamically changes it's resistance when a pressure is applied. FSRs can be used to detect pressure, weight or force, are simple to use and are cheap. The downside to these sensors is however that they are not very accurate; They can be well used to detect ranges of force, but are not very well suited for specific measurements.
When no pressure is applied on the FSR, the resistance is infinite. The force to resistance ratio is not linear, it drops down quickly when a force is applied, after which the curve flattens out (see figure 18b. This non-linearity can however be compensated for in the translation from input to output. An FSR is made up of two different layers, divided by a spacer which is illustrated in figure 18a. The first layer is a conductive polymer, which changes resistance in a predictable manner as force is applied to the surface. This layer is usually a polymer sheet or it is printed on a flexible substrate by screen printing. The sensing film is made up of electrically conducting and non-conducting particles that are spaced in a certain pattern. This pattern is made up of miniature electrically conducting particles, that are placed in such a way to reduce temperature influences and to improve mechanical properties. Applying a force to the surface of the upper layer makes these particles to touch the conducting electrodes, which in turn changes the electrical resistence of the FSR.



(a) FSR structure



(b) FSR resistivity data

Figure 18: Force sensing resistor

In our design we used the Interlink 402 FSR, which is a basic FSR with a range of 0-100N and a pressure sensitive surface area of 13mm. The sensor is only a few mm tall so it can ideally be placed within different devices. The electrical resistance changes from infinite at zero pressure to 200Ω at full . The FSRs can be ordered from the manufacturer directly for about 3€a piece, which also makes them one of the cheapest options from our table.

4.11.1 Translation from sensory input to required output

An FSR is a really basic sensor, it responds to a changing pressure with a changing resistance. The only thing that can be read out from an FSR is this resistance and, as is visible in figure 18b, the resistance is not linear to the applied pressure.
This changing resistance has to be read out in some way and then transferred to the computer as a useful input. For this translation an Arduino nano is used, as the Arduino is a great tool to translate sensor data to a required output.

4.11.2 Initial try out

To validate the functioning of the FSRs, we first made some very early concepts to see if we could get the required measurements. A simple model was built with two FSRs, a breadboard, an Arduino nano, some LED lights and some connective material. This concept was built in such a way that the amount of pressure applied to the FSRs would result in one out of the four LEDs to turn on.
Figure 19 shows the setup used, the arduino code used can be found in *Appendix 6*. When no pressure is applied the arduino only powers LED 1, when a small pressure is applied LED 1 will turn off and LED 2 will turn on, when a bit more pressure is applied LED 2 will turn off and LED 3 will turn on and at even more pressure LED 3 will turn off and LED 4 will turn on. Hard pieces of plastic were placed on top of the FSR to distribute the pressure evenly on top of the FSR.

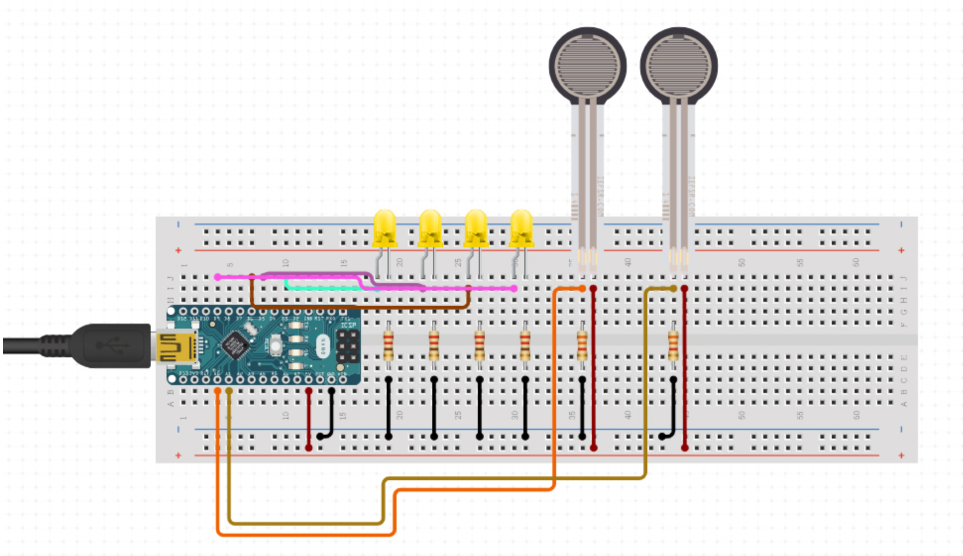


Figure 19: Set up testing FSR

The device turned out to work as expected, all LEDs would turn on and off as required. The only downside to the system was that it was hard to apply the required pressure. We found out that the lack of translation makes it hard to specifically apply a certain force with your finger. Different people were asked to try out the system and their feedback was decisive, because there is no translation and your finger is basically pressing against a hard object, there is no feedback that tells you how much pressure you applied. When the system was tried out again with a piece of foam-rubber on top of the pressure-distributing piece of plastic, it got a bit easier to make the required LED turn on.
From time spent with the ICU physiotherapists I learned that during grip strength testing with a hand dynamometer, a device for measuring maximal grip strength, patients found it hard to keep the device on a constant value. The hand dynamometer does not change shape when squeezed, the device stays solid and so no translation can be felt for a given force. This shows that translation helps in force control feedback.
As both the hand dynamometer as well as the initial try out showed that translation considerably helps in the feedback of force, our final design should have a translation that is directly proportional to the given input force.

4.11.3 Arduino script for grip trainer

An Arduino script has been written to distinguish the different ranges of resistance that follow from a change in pressure on the FSR accordingly. These 4 different ranges; no pressure, little pressure, medium pressure and high pressure then have to be translated to 4 different analog outputs. The output only needs to display whether each level of pressure is reached or not, so that always either of the 3 different outputs is in the "on" position and the others are in the "off" position. When there is no input the elevators in the game will automatically return to their starting position.

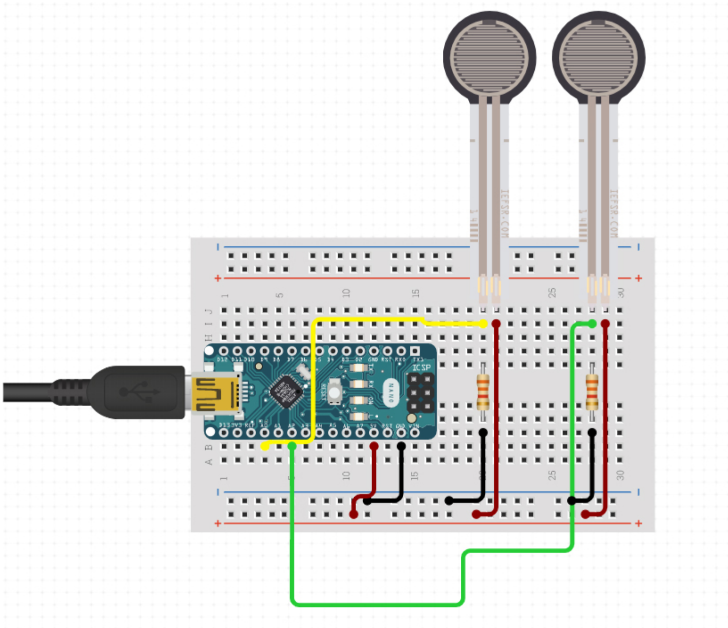


Figure 20: Arduino connection layout

Figure 20 shows how the sensors are connected to the Arduino. The first FSR is connected to A0 and the second FSR is connected to A2. The analog pins (A0-A7) are used for analog input, which in our case is the changing electronic resistance of the FSR. The Arduino code visible in appendix 7 shows how the Arduino translates the analog input to a useful signal that can be used for the game.
The Arduino script has been written in such a way that, if needed, the Arduino code can be quickly changed to accomodate for patients that can only use one hand. In this case only one FSR will be used and the signal is used for both controlling elements in the game.
The values for each of the pressure ranges are set by making use of figure 18b and determining how much input leads to a certain change in resistance. We tried to make each of the ranges reflect an even amount of extra input needed so that the extra force needed to get to the next floor is similar in all the steps.

4.12 List of requirements

A list of requirements is formed using the MoSCoW Method ["Moscow Method", n.d.]. The MoSCoW method is meant to create 4 different sections of requirements ordered by their importance. These 4 sections, Must have, Should have, Could have and Would have should sketch the most important ideas of the project. This method can help in design projects to prioritize the correct parts and not get lost trying to work out small irrelevant details.

Must have

- Grip force control that detects multiple ranges
- Be usable for patients with MRC4- or higher
- Be understandable for patients that are moderately to fully cooperative
- No design features that may cause safety risks for the patient
- Must work in the setting of an ICU room
- Design that eliminates chance of patient to patient cross contamination

Should have

- Big enough monitor for easy visibility
- Patient specific resistance setup
- Easy set-up menu for caregivers
- Work through entire ROM
- Easy to fabricate

Could have

- Wireless control
- Easy set-up so patients can start a game by themselves
- Day to day performance ratings
- Vocal feedback

Would (not) have

- Multiple games, both cognitively as well as physically stimulating
- Different levels within games
- Integration into ICU rooms
- Enough adjustability to be challenging and enjoyable for a large range of patients.

4.13 Game design

The scope of this study never included the actual design the of the video game itself. As this study was bound to certain time restraints, there was no time to build a complete new video game from scratch. Also, as I am a mechanical engineer by origin, graduating as biomedical engineer, I had no experience in building games. However, as it is SilverFit's main product, they already had a whole range of different games we could possibly use. Because of this the games they currently had in their repertoire were scanned to see what the possibilities would be. For the assessment of the individual games there was looked at games that needed multiple inputs as we wanted the patient to be able of using both the left and the right hand.
A list of required features of the games was created:

- Multiple inputs usable
- Not only a "yes or no" type of input
- Easy to understand game-play

Also the controlling mechanism of the games were assessed; games that needed only input or no input were disregarded, the goal was to work with grip control and not only with maximal grip strength. Another important factor was that the game should be relatively simple. As the intended target audience probably does not have their full cognitive functioning, the games should be easy to comprehend and execute.

The most suitable result was found in the "elevator game". The aim of this game is to get the characters from the start position to the correct floor (using your left hand) and after a while of "mining", the characters walk to the other side of the floor to be picked up again and (using your right hand) delivered to the end platform. The characters start the game at the left top and are either dressed in yellow, blue or red, and wear similar color hats. The character's color corresponds with one of the colors of the floors in the middle of the game, which are meant to represent different height mine shafts. On the left side there is an elevator that brings the characters down to the desired height. When the character reaches the desired floor he will be "mining" for 10 seconds before proceeding to the right end of the floor. Then on the right there is a second elevator to bring the characters up to the finish platform.

By adjusting the grip force on the device, the input changes. Zero input force translates to the elevators being at their starting position, soft to medium force will bring the elevators to the first (yellow) or second (blue) floor and a higher force will bring the elevators to the last (red) floor. The maximum exertable force can be adjusted in the options menu to account for weaker or stronger patients and to adapt to the springs used in the device. The forces required to get the characters to each of the three floors are scaled proportional to the maximum exertable force.

Appendix 9 shows multiple visuals of the game. Figure 43 shows the start up screen, which consists of a start button which starts up the actual game. An options button which takes you to the settings menu. An exit button which, obviously, closes the game. And lastly an input selector.
Figure 44 shows the adjustments that can be made in the game. The force needed for maximum input can be changed in steps of 0.5kg (about 5N). Time can be increased by increments of either a minute or a second. The speed at which new characters spawn on the screen can be adjusted and whether or not you want the characters to move can be adjusted by the animation button.
Figure 45, 46 and 47 respectively show the beginning, halfway and ending of the characters through the level of the game.

Sound design

From the past it has been known that the combination of both visual as well as audible feedback yields better results than just visual feedback. The addition of sound feedback improves the participant's performance and may positively increase the mood effects. Rauterberg M., 1994
Audible feedback gives feedback to the player, often in addition to visual feedback. It helps the participant to recognize when something is happening, also when they might have not seen it yet. In this way it can also help give the participant to get more information out of the game, for instance when a new character spawns.

Besides that, audible feedback is also meant to help the participant's feeling of accomplishment. The sounds that are played when a character finishes the game helps the player to recognise the final goal of the game. In this way it can increase the patient's adherence to the game by making the game more pleasurable and fulfilling.

5 Deliver

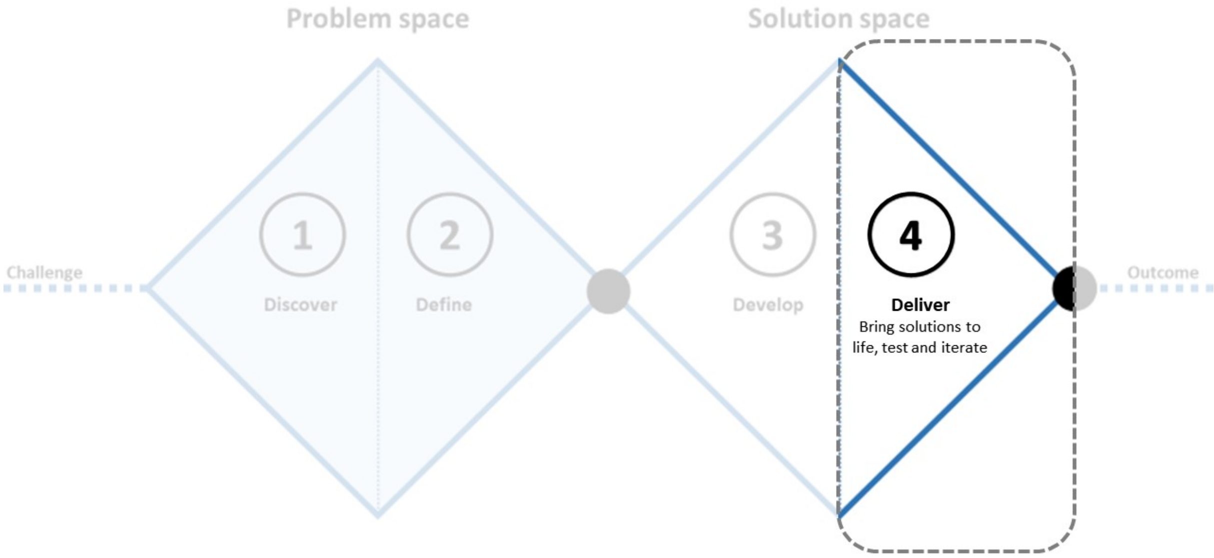


Figure 21: Double diamond design: Deliver

The deliver phase will answer the following sub questions

15. What are the required specifications of the final versions?
16. What methods can be used to assess the concepts?
17. How will these assessments affect new design alternatives??
18. What is the proposed final design comprised of?

5.1 Specification

The input for the final design will be the patient's movements. To stimulate the training of hand control for improved QOL and functionality in ADLs, the input will be from a grasping motion. Different designs will be made for two different grasping types. Section 4.6 shows why the decision for these two different grasps were made.

The first grasp will be the medium wrap, which is the most used grasp in ADL. The medium wrap is normally used to hold on to long but narrow objects, i.e. a vacuum cleaner, a bottle, a cup or the handrail in public transport. To design for this grasp form, a device will be made that works at least through the functional range of motion of the MCP and PIP joints. Figure 14 gives a better representation of what the required ROM is.

The second grasp will be the power-sphere. This grasp is normally used to hold round-ish objects. For instance when eating an apple, using a stress-ball or picking up laundry. To design for this grasp we need to work through a different range of motion. We will design a device that is similar in size to daily usable objects, to aim at rehabilitation for real life situations. See figure 14

The exertion of power in each of these grasps has to be translated into a force to be read by the sensor in some way. For inspiration we first started looking at existing hand grip trainers. From earlier research and personal testing we already knew that we needed a device that converts force into a directional translation, as this increases the accuracy of power delivery for the user.
When studying available hand grip trainers, we noticed that currently available examples are designed for people that are stronger than the average ICU patient. Because these models are usually not designed to have a lot of adjustment, they are unusable for most ICU patients. Besides that, they are not designed to keep the risk of cross-contamination between patients to a minimum, nor are they designed to be be used as a controller for a video game.
In the past there have been some devices have been created to incorporate some sort of grasp movement as the input for a video game and many modern game controllers still require hand power to press the buttons and move the joysticks. A nice example used in the past is the old NES zapper, which was used for shooting ducks on your television screen 22. This game used a trigger grasp to control the shooting of the gun. This game was however never meant to be used for rehabilitation purposes and neither are the modern controllers that

Figure 22: NES zapper

For the medium wrap we decided to make a device which would fit in the palm of the hand, and utilizes a pushing mechanism that can be pushed upon with the proximal and middle phalanxes. This way the device can be used through at least the entire functional range of motion. As the design utilizes the same working principals as regular grip trainers, we will call this concept the grip trainer from now on.

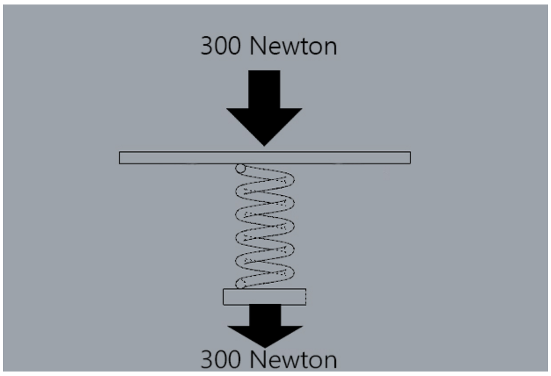
For the power-sphere we wanted to make a device that is similar to the stress balls that are currently already used on the ICU. The stress balls currently used do not offer any form of feedback but are, according to the physiotherapists, a device that the patients usually like in terms of size and feel. Another advantage is that there is a huge variety in stress balls, ranging from soft to hard and from big to small. For these reasons we decided to utilize regular stress balls as the base for our power-sphere design. From now on we will call the power-sphere concepts the stress-ball concepts.

5.1.1 Required power

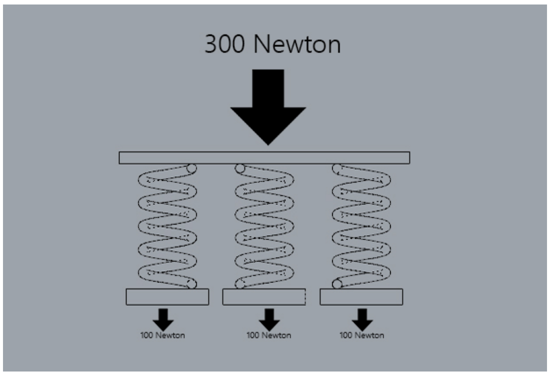
Because of the wide range of maximum exertable grip force present in ICU patients, designing one single device that can accommodate for grip strengths between 0 and 400N would be very complex. Therefor the decision has been made to make a design that can not be adjusted, but instead uses different solutions to suit the required stiffness for the patient. The main advantage of this is that for each patient there may be a device that is specified for their needs. For the medium wrap this comes down to creating a device that can incorporate different stiffnesses of springs. For the stress-ball concepts we can use different density foams to create a variety of required maximum grip forces.

As the FSR used in our concepts is able of measuring anywhere between 0 and 100 Newton, the device can not suffice with only one stiff spring. This is because, when a patient is able of exerting 300 Newton and a spring is used that needs 300N to be compressed fully, the patient can only use one third of the working range. If they go over that third, the force exerted on the FSR exceeds 100N, and the FSR will only register this as ”maximum force”. It can not make any differentiation in force when the force is over 100N anymore.
A solution for this might be to use multiple springs with a lower stiffness. For example; when 3 springs are used parallel to each other. If the patient is able of exerting 300N, this 300N gets spread over the three springs, leading to 100N per spring. The FSR is able of reading a maximum of 100N, so the entire range of motion can be used if the FSR only reads the force from 1 of the springs. Patients with less power can then use a device with softer springs or less springs installed. With this method it gets easier to adapt for the patient’s maximum exertable force and so to give them the device that is the most useful for their personal rehabilitation.

Figure 23 shows how the force gets distributed with either 1 or 3 springs when the same force is applied. If the FSR is placed under one of the springs in figure 23b, it would read a force of 100N for the given force on top. If the FSR would be placed under the spring in 23a, it would read a force of 300N for the given force on top.



(a) Single spring force distribution



(b) 3 springs force distribution

Figure 23: Force distribution between 1 or 3 springs

5.1.2 Grip trainer concept inspiration

For the grip trainer concepts we first studied pre-existing grip trainers that are commercially available. Most of these concepts made use of one large torsion spring. These torsion springs would not be the best solution for our study. The springs are big, not easy to adjust to stiffness and usually quite expensive. Also, it would be very hard to use the FSR in this configuration as there is no usable spot to put it and the torsion spring does not add any linear pressure.

Some commercially available versions made use of compression springs in their design. This would be the best basic concept to use with an FSR, the design would be easy to adjust for hand size and grip force, seemed to work well with rapid prototyping and does not require the use of large and expensive springs. Compression springs are therefore used as the basic working mechanism for our first concepts.

5.2 Analysis

After each concept an analysis is done to reflect on all the good an bad things of said concept. The analysis consists of a SWOT analysis, used to help with identifying Strengths, Weaknesses, Opportunities, and Threats related to each individual concept. It includes a descriptive figure of the device where all the components are named and can be seen. And then below there is a description of the device, the findings during preliminary testing and the lessons learned from the concept that can be used for designing the next iteration.

5.3 Grip trainer version 1

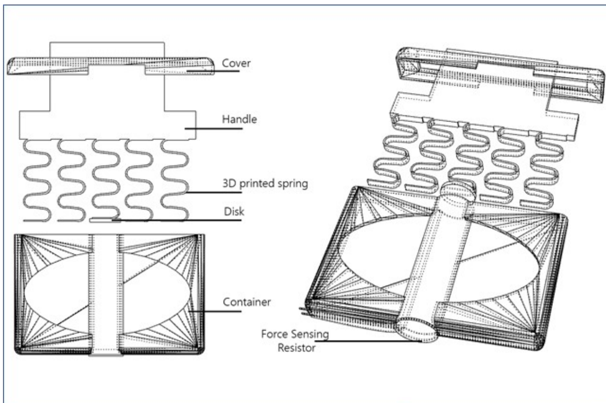
5.3.1 Grip trainer version 1.1

The first concept, version 1.1, was designed to be completely 3D printed and with as few separate components as possible. In the model there are 5 separate compression springs placed in a line and which are connected to a handle. Below the middle spring an FSR can be placed to measure the exerted force, which in term controls the game. This handle and spring combination can slide vertically inside the container. By applying force on the handle the springs are compressed and the handle is lowered in the container. The handle is held in place by a cover on top of the container, which keeps the entire construction in it's place. By pressing the handle the force on the springs increases, which then increases the force on the FSR.

After initial testing we got the following results:

- The first problem was that the springs, which were basically designed as a 2D version of a helical spring, tended to buckle.
- The second problem was that there was too much play between the handle and the container, which caused the handle to wiggle around.
- Lastly, in the design there was not enough time spend on ergonomics and safety. The concept was uncomfortable to handle and the corners were too sharp.
- The basic working mechanism of the concept works quite good. The idea could be adjusted and usable for the final product.

Figure 24 shows the entire analysis of grip trainer version 1.1.



Strengths	Weaknesses
- Springs work okay - Mechanism seems to work good - FSR reacts to compression of the handle - Spring stiffness can be adjusted by changing the spring diameter	- Springs tend to buckle under load - Container walls are thin and brittle - Hard to determine exact spring stiffness of plastic springs - Handle moves around inside container too much
Opportunities	**Threats**
- Mechanism can be used for further development - FSR in the system works and shows force exerted - Subdividing springs may stop buckling	- Too much play in the system - Buckling and jamming of the springs - Breaking of the container - Lots of post processing of the springs needed

Description	Findings	Lessons
Version 1.1 features a handle with 5 springs attached to it. The handle can slide inside a container when pressed, by pressing the handle the springs are compressed. The middles spring presses on the FSR which is placed on the bottom of the tube in the middle of the container.	• Mechanism works. FSR reads out different values for different force • A lot of play between handle and container • Plastic springs tend to buckle • Buckling of springs can lead them to jam • Handle has sharp edges	• Create way of stopping the springs to buckle • Mechanism can be used for further prototypes • Sharp edges of handle should be discarded

Figure 24: Analysis grip trainer version 1.1

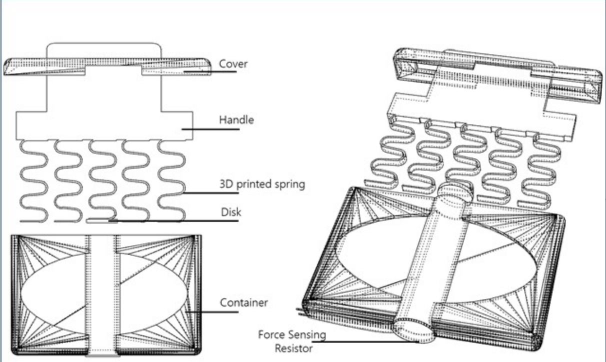
5.3.2 Grip trainer version 1.2

Grip trainer version 1.2 is a revised version based on the basic design of version 1.1. The biggest flaws of version 1.1 have been redesigned to come up with a better concept. Version 1.2 utilizes the same container and handle design as version 1.1 and also features the same design of 3D printed springs connected to the handle. However with this version the ergonomics were improved as all the edges on top of the handle are now rounded. Also the fitment of the handle inside the container was improved to reduce the play in the system.

After initial testing we found the following results:

- During post-processing the shell of the container turned out to break easily. This could be fixed by designing the device with a thicker outer wall for the container or by using shapes that can withstand forces better.
- There is still some play in the system. Possibly the surface area where the handle slides on the container wall is too big.
- The buckling of the springs and the problem with the play get in the way of a good working final version. Because of this, this design will be discarded after this iteration.

Figure 25 shows the entire analysis of grip trainer version 1.2.



Strengths	Weaknesses
- Springs work okay - Mechanism seems to work good - FSR reacts to compression of the handle - Spring stiffness can be adjusted by changing the spring diameter - Round edges of handle	- Springs tend to buckle under load - Container walls are thin and brittle - Hard to determine exact spring stiffness of plastic springs - Handle still moves around inside container too much
Opportunities	**Threats**
- Mechanism can be used for further development - FSR in the system works and shows force exerted - Subdividing springs may stop buckling	- Too much play in the system - Buckling and jamming of the springs - Breaking of the container - Lots of post processing of the springs needed

Description	Findings	Lessons
Version 1.2 is a revised version of V1.1. The edges on the handle have been changed to make it ergonomically more usable. The handle has been widened to decrease the play between the handle and the container.	• Springs still buckle. • Smooth handles are better and widening reduces some of the play. However there is still a lot of play in all directions due to the design of the handle and the container.	• Because of the downsides of this prototype this design will be discarded. • The mechanism of this version works quite good so next versions will use the same basic principle. However with a new design to reduce play.

Figure 25: Analysis grip trainer version 1.2

5.4 Grip trainer version 2

5.4.1 Grip trainer version 2.1

Grip trainer version 2.1 only shares the same basic mechanism as the previous versions, all other parts of the concept have been completely redesigned. The flat coil springs were discarded in favor of 3D printed helical coil springs to prevent the risk of buckling that was present in the flat coil springs. For every spring a separate piston was created and each piston now includes it's own cylinder to reduce play in the system. The coil springs are now separate parts that drop into the cylinders.
Each piston is attached to the a handle by two rectangular beams. All cylinders are interconnected via a 3D printed container construction. On the bottom of the middle cylinder the an FSR is placed to register the force exerted on the handle.

After initial testing we found the following results:

- Version 2.1 seems to work a lot better than the initial concept. The excessive play from the previous versions is now gone by using 3 different parts that share the bearing necessity.
- The force needed to fully compress the device is over 400N, this is too much for the average ICU patient and so the spring stiffness should be reduced.
- The device is only usable for people with very large hands. The device should be scaled down to be usable for a larger target audience.
- The 3D printed coil springs require a lot of post-processing. For now they do seem to work okay but in the future a better solution may be needed.
- The springs also feel brittle. They might break during the game.

Figure 26 shows the entire analysis of grip trainer version 2.1.

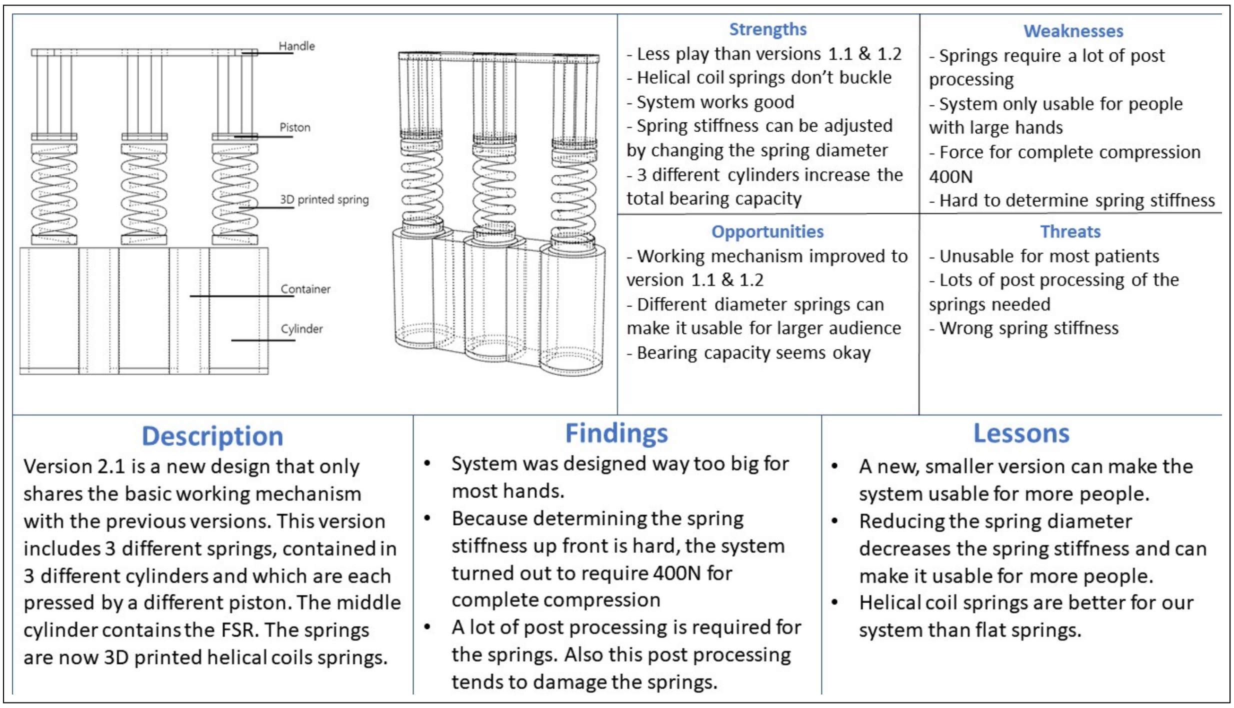


Figure 26: Analysis grip trainer version 2.1

5.4.2 Grip trainer version 2.2

For Version 2.2, which is basically a re-designed version of version 2.1, we used springs with a thinner diameter to reduce the spring stiffness. One of the problems with 3D printing the springs is that it is very hard to determine the exact spring constant, so we could not calculate the spring stiffness before the springs of version 2.1 were created. For version 2.2 we also reduced the scale of the concept to make it suitable for people with smaller hands.

After initial testing we found the following results:

- The force needed for full compression is now 200N which is more acceptable than V2.1. However it is hard to determine the exact spring constant of the 3D printed springs before printing.
- Because of the difference in outer diameter of the pistons and inner diameter of the cylinders there is still quite a bit of play in this concept. Further concepts will have to proof whether this will be a problem or not.
- During post processing some of the springs broke. After this version we are discarding the 3D printed springs because the disadvantages do not outweight the advantages at this point.

Figure 27 shows the entire analysis of grip trainer version 2.2.

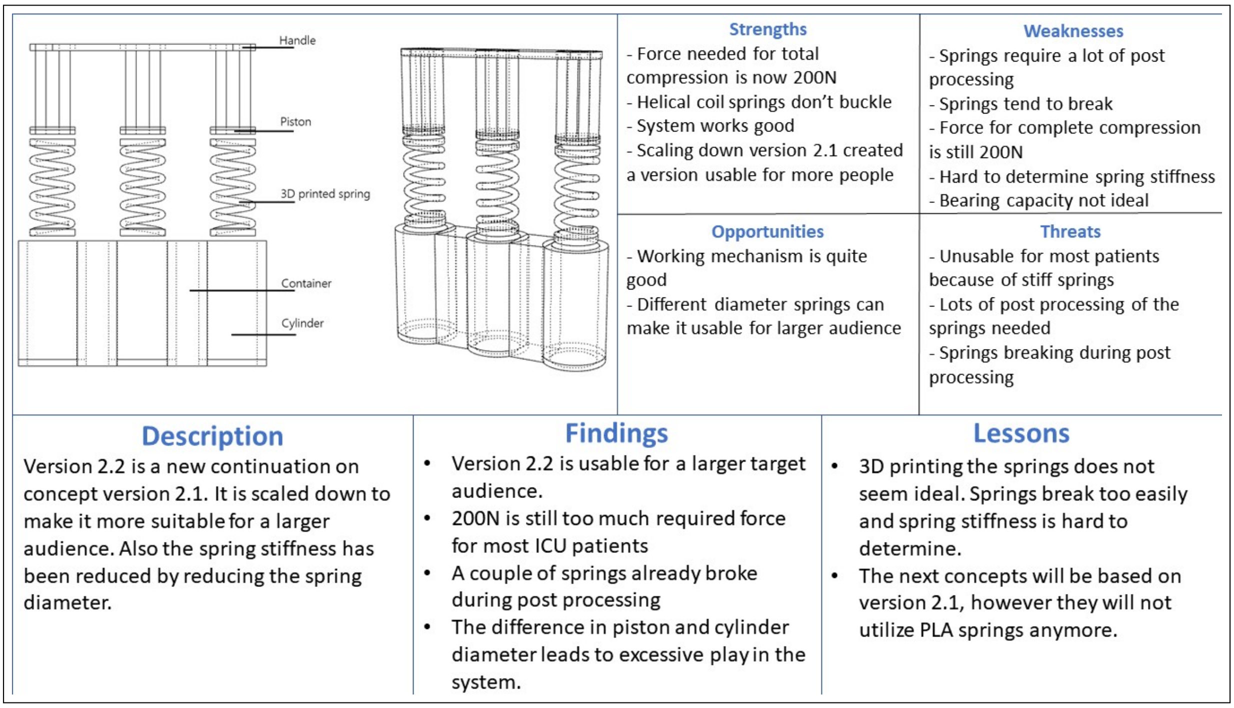


Figure 27: Analysis grip trainer version 2.2

5.5 Grip trainer version 3

The 3D printed springs all gave a lot of problems because of the material they were made of. The springs were made of PolyLactic Acid (PLA), which is a biodegradable plastic. The problem with this plastic is it's flexibility; it's only elastic for a small range after which it will break. For this reason we decided to swap the PLA springs with metal ones, which we borrowed from Remote Controlled (RC) cars. These RC car springs can be found in a huge variety of stiffness, length and diameter which meant that playing around and testing different ones is really easy. They are also widely available so a variety can just be ordered and they do not have to be made specifically for this research.
Even though the springs can be ordered in such a wide variety, they still have a minimum stiffness which could make the design unusable for some patients. For this reason in V3 there are also designs that allow the use of only 2 or 1 spring. The versions with either 1, 2 or 3 springs will from now on be called V3.11, V3.12 and V3.13 respectively.
When designing 3D printed springs for the earlier versions, we made the springs connected to a small round plate, which made sure that the force on the spring would be equally distributed on the FSR. With the metal springs we do not have this option, that is why an extra, round, 3D printed disk is placed between the spring and the FSR. This disk makes sure that all of the force on the spring gets distributed equally on the FSR.
Another change to the last version is that the designs are made smaller than they were in V2.2. Because of the minimum diameter required to make the PLA springs work, the designs of V1 and V2 became quite bulky. The metal springs work a lot better than the PLA springs did, and can have a smaller diameter so the design can be made more compact. After initial testing we found the following results:

- These designs seem to work rather well. The metal springs have a more consistent stiffness than the PLA ones and require no post-processing.
- The 3D printer works by building small layer on top of each other. Because each layer is fluid when layed down, they tend to sag out a bit. This gives leaves small ridges in the concept as it comes out of the 3D printer. Figure 30 shows a detailed close up picture of these lines left over from the 3D process. When these ridges are in the same direction on the piston and the cylinder, post-processing is needed to smooth them out and make sure the piston does not jam in the cylinder.
- These versions were tested with the FSR and the results were promising. The elevator game was played succesfully with healthy participants. For this reason these designs will now be tested on the ICU with actual patients.

5.5.1 Grip trainer version 3.11

Design V3.11 was the first design we decided to test with actual patients on the ICU. The decision to first test the design with only 1 spring was made because we were unsure of the patients that were available and willing to help in testing. Because of this unknown we could not measure or calculate the maximum grip force for each patient up front, so we decided to build a few concepts of V3.11. The springs used had a stiffness of 4N/mm, which meant that a force of 100N, the maximum force the FSR could read out, was reached at 25mm compression. With a spring length of just over 30mm and a compressed length of 5mm, the length to stiffness ratio was ideal; no compression leads to no force and a relaxed system, full compression leads to (at least) 100N of force and a completely compressed system.
Because the game was set up so that it can be adjusted to the patient's specific strength, there was the possibility to set the game up so that patients who could only apply a force of for instance 50N could still reach all levels of the game. This is however not the ideal setup; preferably a patient with a maximum grip strength of 50N would use a spring with a stiffness of 2N/mm, so that full compression would lead to 50N of force.
After testing with ICU patients we found the following results:

- V3.11 does not have enough bearing capacity. As pressure is distributed equally on the top of the handle, there is no problem and the piston will slide through the cylinder without any problem. However, when the pressure is not distributed equally and more pressure is exerted on one end, the system tends to bind up. The piston will then be pushed into the wall of the cylinder instead of downward, and will jam. ICU patients showed to have problems distributing their force equally along the top of the pushing device, which meant it jammed often, leading to frustration with the patient. Before the design was made no real studies were done on the distribution of power between the little, ring, middle and index finger. It turns out that in medium wrap people tend to use the little finger a lot more than the other fingers, which can be seen in figure 28.

- Another problem that got clear during testing with ICU patients, was that there was too much play in the system. This excessive play made it easier for the piston to move around in the cylinder, causing the system to jam.

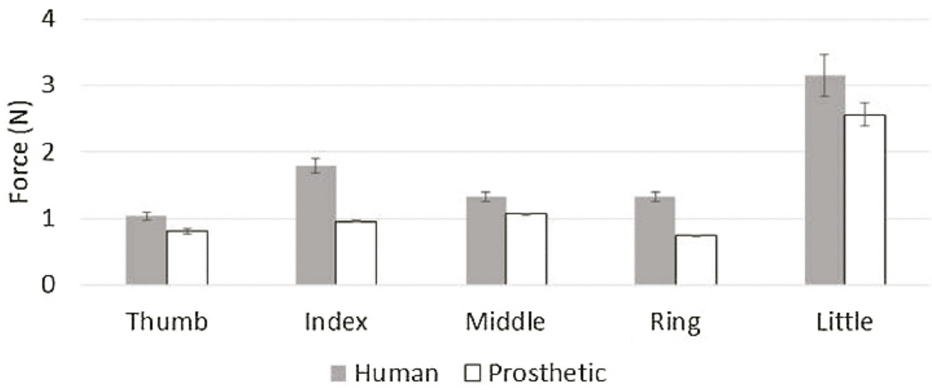


Figure 28: Distribution of power in medium wrap

Figure 29 shows the entire analysis of grip trainer version 3.11.

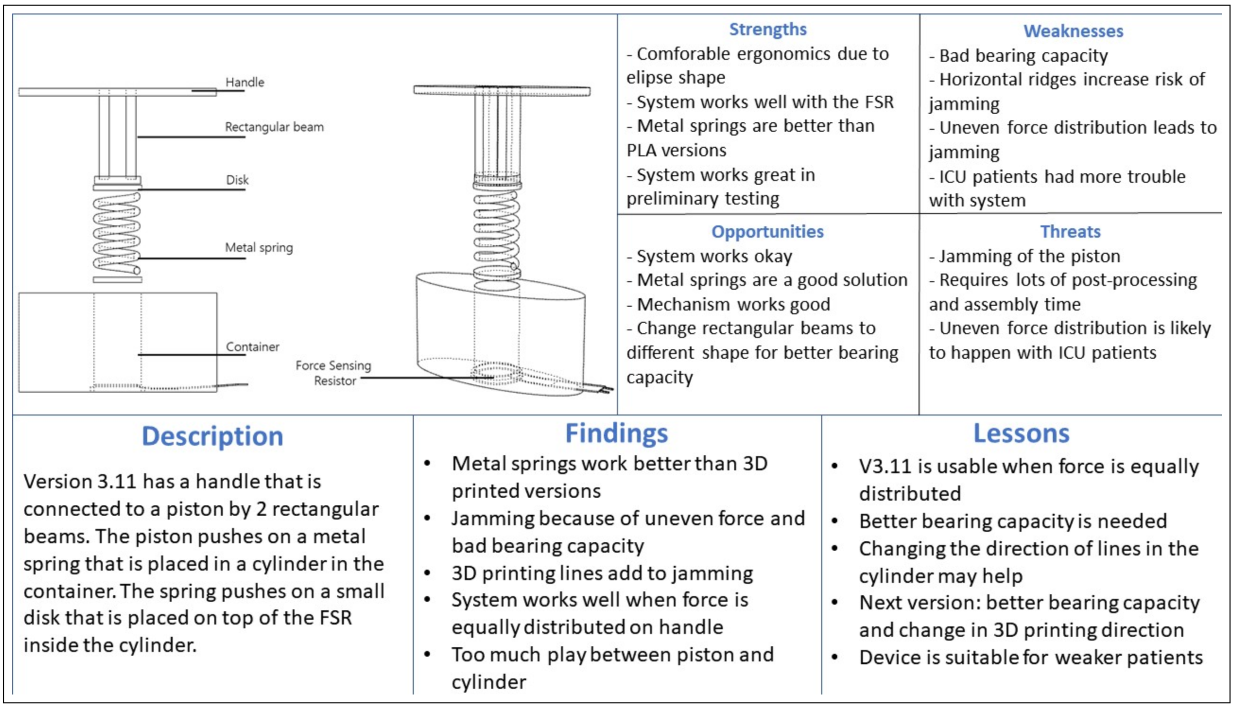


Figure 29: Analysis grip trainer version 3.11

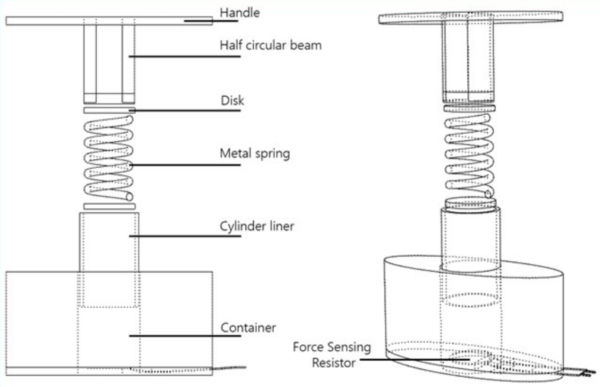
5.5.2 Grip trainer version 3.21

The design of V3.11 consists of a piston section, which is connected to the handle by two rectangular beams visible in figure 29. These beams are made this way so that a piece can be placed in between them that holds the whole system together. However, this leads to excessive play as only the piston now takes care of the bearing capacity. For a next version the two beams are replaced with half-round beams with the same outer diameter as the piston, see figure 32. By doing this we replace the small piston with a piston that spans the entire length of the cylinder wall and so increases the bearing capacity.

Figure 30: Lines in the 3D printed model

When version 3.11 was tested with ICU patients, a lot of jamming was noticed. The reasons for jamming could be traced back to excessive play in the system, but also to the horizontal lines that were left in the cylinder by the 3D printing process. Figure 30 shows how these lines are visible on the cylinder wall. For this reason, a new addition to design V3.21 is the addition of a cylinder liner. This cylinder liner is 3D printed, but is placed on it's side during printing. This leads to the lines in the final 3D printed model being vertical instead of horizontal. These vertical lines should reduce the chance of the piston jamming in the cylinder as the piston now does not move perpendicular to the ridges anymore. Simply printing the whole concept horizontally would have been an option as well, however with the 3D printer available to us this would require the model to have supportive material in a lot of places, making it harder to end up with a smooth final result.

Figure 31 shows the entire analysis of grip trainer version 3.21.



Strengths
- Comforable ergonomics due to elipse shape
- Bearing capacity better than V3.11
- Addition of cylinder liner works well

Weaknesses
- Stil not great bearing capacity
- Uneven force distribution leads to jamming
- ICU patients had more trouble with system than preliminary testing with healthy participants

Opportunities
- System works okay
- Metal springs are a good solution
- Making the same design with other techniques than 3D printing may create a better usable device.

Threats
- Jamming of the piston
- Requires lots of post-processing and assembly time
- Uneven force distribution is likely to happen with ICU patients

Description

Version 3.21 is a continuation of V3.11. In this version a cylinder liner is added to overcome the problems created by the lines left over from 3D printing the cylinders. Another improvement is the change from rectangular to half-circular beams. These increase the total bearing surface of the system.

Findings

- Metal springs work better than 3D printed versions
- Addition of cylinder liner makes the movement smoother
- Uneven force distribution still causes some problems
- Increasing the bearing surface helps system as well

Lessons

- V3.12 is a decent improvement to V2.11; movement is smoother and there is less play in the system
- This type of 3D printing may not be able to create the desired properties to have the system with 1 spring work as required.

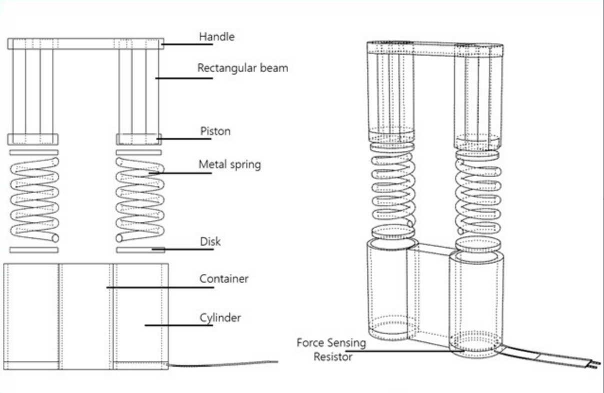
Figure 31: Analysis grip trainer version 3.21

5.5.3 Grip trainer version 3.12

Version 3.12 utilizes the same basic principles as V3.11 and V3.13. I has the same general design as V3.13, but there is one spring, container and piston less than in V3.13. This means that V3.12 could be useful for patients that are too strong for V3.11 but not strong enough for V3.13.
After initial testing we found the following results:

- The addition of an extra piston and cylinder adds to the overall stability of the system. There is less play than in V3.11.
- There is still play in the system, and when the force is not equally distributed on the top of the handle, the pistons still tend to jam in the cylinders.
- After testing we found no real extra use for a version with 2 cylinders instead of 1 or 3. With stiffer springs in V3.11 or softer springs in V3.13 the same overall stiffness can be achieved. For this reason we will no longer continue developing V3.12 to any newer versions.

Figure 32 shows the entire analysis of grip trainer version 3.12.



Strengths	Weaknesses
- Comforable ergonomics - Design suitable for slightly stronger ICU patients - System works well with the FSR	- Bearing capacity slightly better than V3.11 - Horizontal ridges increase risk of jamming - Not that much improvement compared to V3.11
Opportunities	**Threats**
- System works okay - 2 spring makes it usable for slightly stronger patients - Mechanism works good	- Jamming of the piston - Requires lots of post-processing and assembly time - No real extra benefits next to the 1 and 3 spring versions

Description	Findings	Lessons
Version 3.12 uses a handle with 2 pistons in a row, that compress 2 different metal springs which are placed in 2 cylinders inside a container. When the handle is pressed the force on the springs increases, which in turn increases the force on the FSR that is placed inside one of the cylinders.	• Metal springs work better than 3D printed versions • Slightly less jamming than V3.11 • Lines left by 3D printing cause some jamming and hamper smooth movement • No real extra benefits compared to V3.11 and V3.13	• V3.12 will be discarded as there is no real extra benefit compared to V3.11 or V3.13. The version with 3 springs works better and the version with 1 spring might be a good addition for very weak patients. This version with 2 springs adds little extra.

Figure 32: Analysis grip trainer version 3.12

5.5.4 Grip trainer version 3.13

Version 3.13 uses the same metal springs as used in V3.11. The basic design is very similar to V2.1 and the entire working mechanism is exactly the same. V3.13 has 3 cylinders in a row, an FSR can be placed in the middle of these 3 cylinders. In every cylinder is a metal spring, which can be compressed by either one of the 3 pistons. Each piston is lined up in the same way as the cylinders and connected to the handle via the same rectangular beams as have been used in V3.11. The handle can be pressed to compress the whole system, which then increases the force on the FSR by $\frac{1}{3}$ of the total force exerted on the handle. After initial testing we found the following results:

- The system with 3 cylinders and pistons is a lot less susceptible for jamming. The addition of 2 extra pistons in comparison to V3.11 adds a lot more bearing capacity and less possibilities for the system to move around.
- The lines in the concept that are formed by 3D printing are still hampering the pistons from moving completely smooth up and down through the cylinders. The use of cylinder liners inside the cylinders might be a solution in this version as well.
- The shape of the system does not seem to be ergonomically perfect. The edges of this version are smoothed during post processing, but there might be a better way of creating smooth edges during the 3D design process.

Figure 33 shows the entire analysis of grip trainer version 3.13.

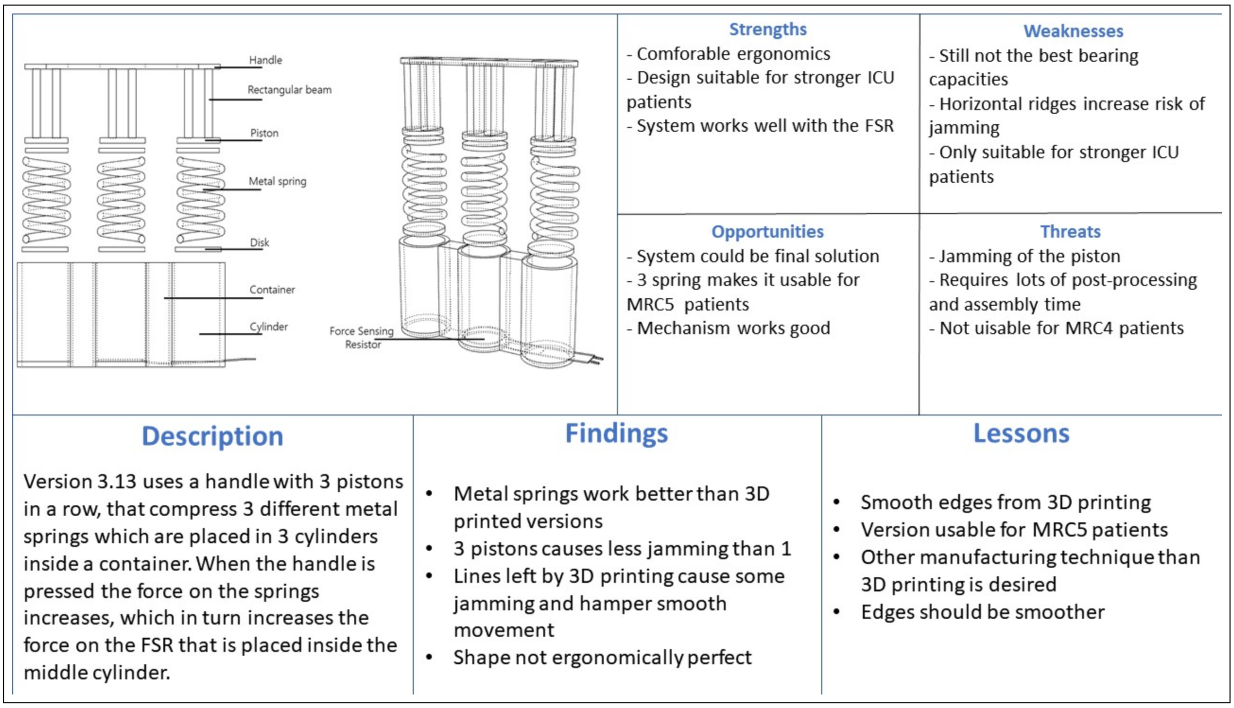


Figure 33: Analysis grip trainer version 3.13

5.6 Final grip trainer design

The final design for the grip trainer is basically a revised version of version 3.13 and could well be qualified as version 3.23. It utilizes the same working principle that has been used since V2. It uses metal springs, has 3 cylinders placed in a row and all cylinders have separate cylinder linings for better bearing capacity and less chance of the pistons jamming. The pistons are connected to the handle by half-round beams with the same diameter as the piston so they exactly fit into the cylinder liners. This way an optimal bearing capacity of the pistons in the cylinders can be created.
On the bottom of the inner cylinder there is space to place the FSR. An opening below the middle cylinder has also been created to guide the wires, that are connected to the FSR, out of the device. The flat wires are guided to the end of the device where a plug is placed to attach the FSR to the Arduino. This way the FSR's wires are not hampering the patient when using the device.
The edges of handle and the container are all smooth and rounded to increase the holding comfort and ergonomics and at the same time minimising the risk of the patient getting hurt by any sharp edges.

After initial testing we found the following results:

- The final version has the best bearing capacity thus far. However the material coefficients of PLA are still not the most suitable for this application.
- The use of 3 springs in a row makes the device not suitable for the weakest patients in our target audience. There is a minimal stiffness to the springs that were commercially available, to make the device compatible for the entire target audience springs should be fabricated with a lower stiffness.
- The problems that were found with unequal distribution of pressure on the handle are mostly gone due to better bearing capacity of the entire device.

Figure 34 shows the entire analysis of the final concept of the grip trainer.

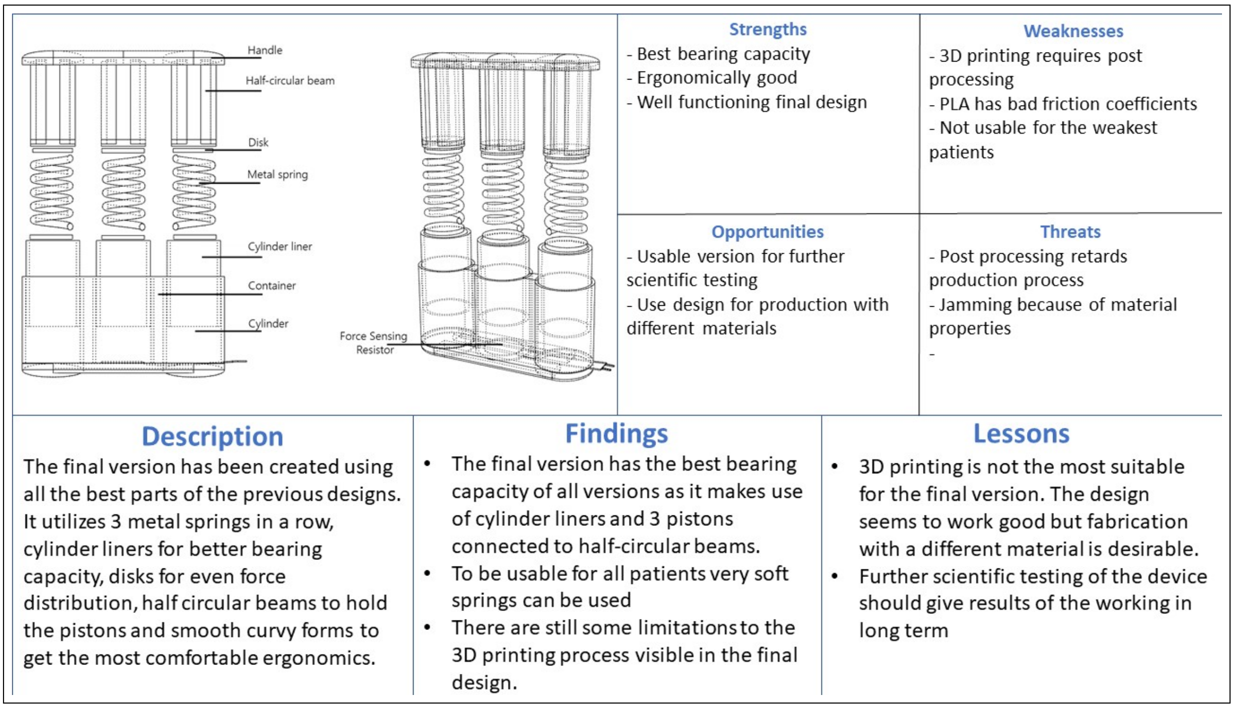


Figure 34: Analysis grip trainer final version

Figure 35 shows the device in both a frontal and a $\frac{3}{4}$ frontal view.

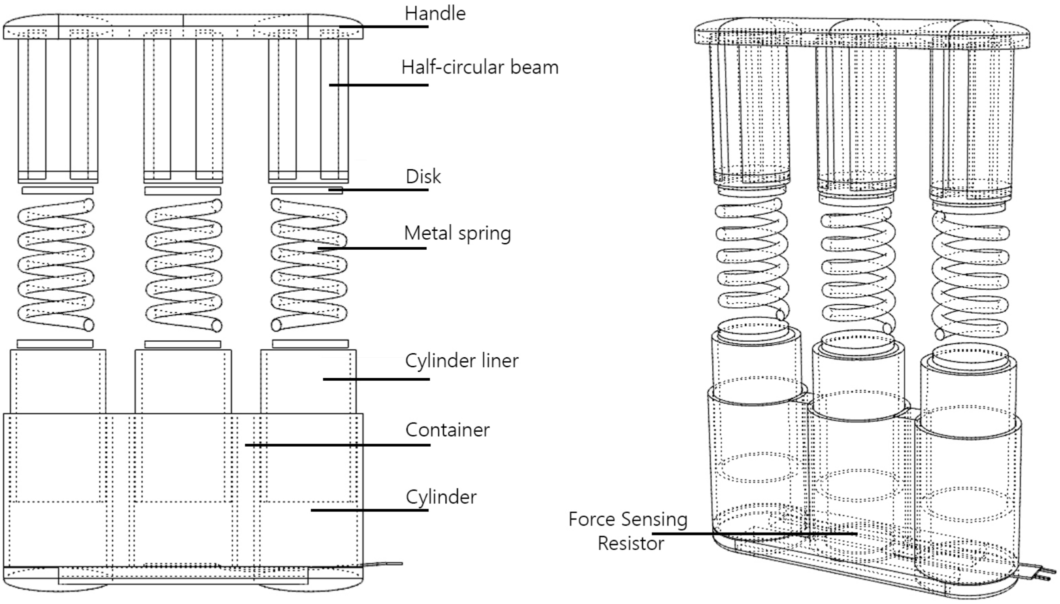
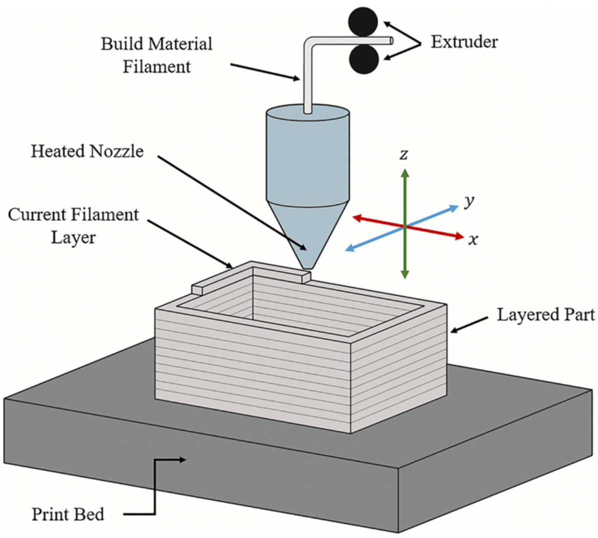


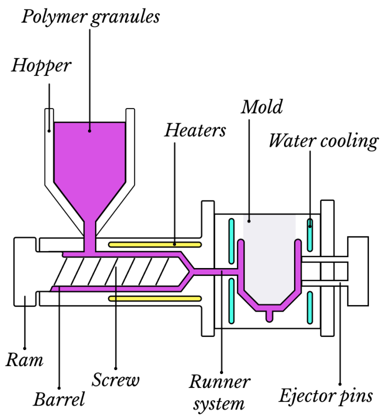
Figure 35: Final version grip trainer

5.7 3D printing shortcomings

3D printing is one of the best ways for making quick and easy prototypes, which is why it is sometimes called rapid prototyping. It is great for making difficult 3 dimensional shapes that would be hard to create with more conventional methods. Making different molds to make each single concept with extrusion methods would be an expensive and time consuming task and would leave very little room for error.
We had the possibility to make use of several Ultimaker 2+ 3D printers "Ultimaker 2 plus", n.d., which were present at the industrial design engineering faculty of the Delft University of Technology. These printers make use of material extrusion as their working mechanism. 3D printing via material extrusion builds the model by extruding a small layer each time. These small layers are all stacked on top of each other to form the final model. This is one of the most used and easiest ways of 3D printing, but the downside to this form is that there will always be tiny ridges in the material (see figure 30.
Ideally the concepts would be created using a technique like injection molding. Injection molding can create plastic parts that require very little post processing and have completely smooth walls. They can be created with many different materials, so a material like Ultra High Molecular Weight Poly Ethyleen (UHMWPE), delrin or nylons can be used to increase the bearing capacity of the device. This would lead to smoother functioning concepts than we were able to create with the 3D printers.
Figure 36 shows the material extrusion 3D printing technique on the left (36a) and the injection molding technique on the right (36b)



(a) Material extrusion 3D printing



(b) Injection molding

Figure 36: Fabrication techniques for concepts

5.8 Stress-ball concepts

The design of the concepts based on the stress-ball design was a lot easier than that of the grip trainer concepts. The idea of the stress-ball concept came from the current use of stress-balls for rehabilitation on the ICU, but also in physiotherapy on different wards in the hospital. Stress-balls are a popular form of exercising as they are cheap, small and easily usable. Patients often get them with the assignment to squeeze them a number of times per day, to train grip strength and increase hand performance.
A stress-ball is made from a latex or polyether, which is molded in a spherical shape. The inner layer is foamy and the outer layer is smooth. The foam inside the ball makes sure that it is easily compressible, while the smooth outer layer makes sure that it does not fall apart.
When the ball is squeezed, the density increases and the stiffness rises. Placing an FSR in the middle of a stress-ball can then be used as our first concepts to test the feasibility.

5.9 Stress-ball version 1

As the basic design of the stress ball is something that is hard to improve, we initially decided to not even try to do so. As sometimes simplicity is key, a variety of different commercially available stress balls were collected. These balls were then cut in half and FSRs were placed inside. Two different initial versions were tried.
The basic commercially available versions of stress-balls, already checked off most of the must haves from the list of requirements. From the Must have list, the stress-balls already has all but one of the features. The softest stress-balls can be used for patients with MRC4 or MRC4+ and harder ones can be used for patients with MRC5. Patients with an MRC score that would be qualified as 4- might not be able to fully compress the softer stress-balls that are commercially available.

5.9.1 Stress-ball version 1.1

For the first tests of the stress-ball concept, just a basic round stress-ball was used and cut in half to make room for the FSR. The FSR was placed inside and the ball was glued back together.

After initial testing we found the following results:

- Because the FSR has a certain thickness, the two halfs of the stress-ball were constantly pushing on the FSR. This lead to a preload on the FSR which made the concept not usable with the original Arduino code. The elevators never returned to their original spot and so no characters appeared in the game. This could easily be solved by either making some space inside the stress-ball for the FSR to fit without pressure, or by rewriting the Arduino code.
- The pressure on the FSR does not get distributed equally, making it hard to dose the required force to move the elevators in the game. Possibly adding a hard bottom and cover to the FSR could solve this.

Figure 37 shows the entire analysis of stress ball version 1.1.

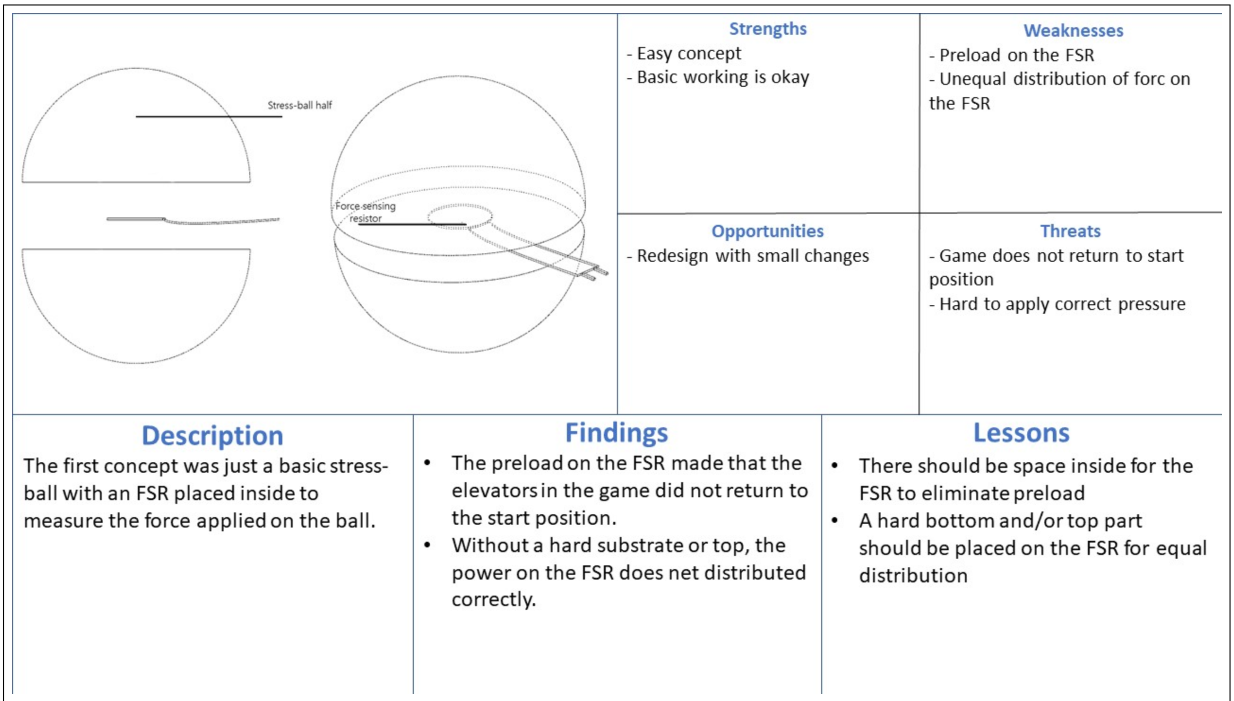


Figure 37: Analysis stress-ball version 1.1

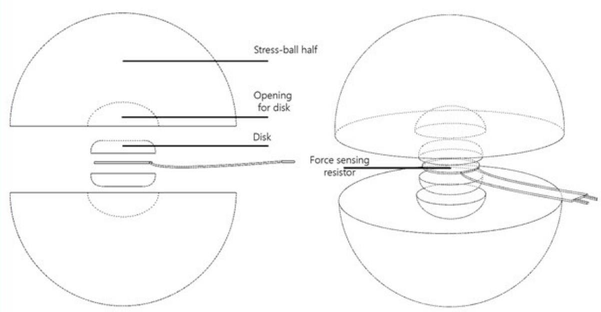
5.9.2 Stress-ball version 1.2

With the knowledge gained from version 1.1, a new stress ball concept was made that allowed room for a 3D printed cover and bottom for the FSR and allowed more room for the FSR to be contained without preload on it.

After initial testing we found the following results:

- As there is now room for the FSR to sit, there is no more preload in the device.
- The hard cover and bottom on the FSR are a useful addition as the force on the stress-ball is now distributed more equally on the FSR.
- Squeezing the stress-ball in any other way than perpendicular to the FSR leads to strange results in the game. This may deliver problems when testing with patients.
- For healthy test participants it is easy to redistribute their power so that it the force is perpendicular to the FSR. However, when tested with patients on the ICU it showed that they automatically squeeze the ball with the power-sphere grasp. This did not deliver the required results.

Figure 38 shows the entire analysis of stress ball version 1.2.



Strengths
- Easy concept
- Distribution of power on FSR is better than in version 1.1
- No more preload on the FSR

Weaknesses
- FSR only measures perpendicular force
- When using proper power-sphere grasp, force is not perpendicular to the FSR

Opportunities
- Works for healthy adults
- No preload makes it usable for the game

Threats
- ICU patients have a hard time delivering the force correctly
- The desired grasp form does not deliver the required result

Description

The same concept as in V1.1 was used, however this time two hard disks were placed as the bottom and cover part for the FSR. These disks help distribute the power equally on the FSR.

Findings

- The disks help to distribute the power equally
- The openings made in the ball make sure there is no preload on the FSR
- Utilizing the right grasp does not give the desired result on the FSR

Lessons

- The FSR might not be the right sensor for this application as it needs perpendicular force, which is not delivered in the power sphere grasp.

Figure 38: Analysis stress-ball version 1.2

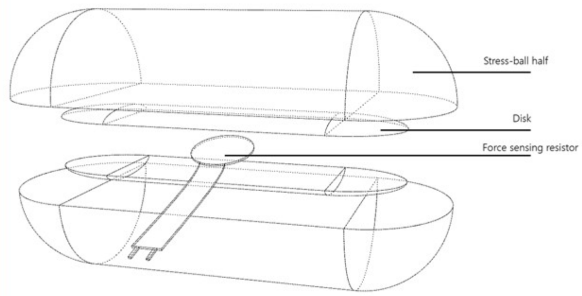
5.9.3 Stress-ball version 1.3

For the third version of the stress ball we used a capsule shaped stress-ball. This stress-ball uses a grasp that is not completely true to the original idea of the power-sphere grasp, but the design was made to see if the stress-ball concept could work with the FSR. As the capsule shape will automatically be squeezed more horizontally instead of distributing the power all over the sphere, chances are that it gives better results.
The design uses the same basic design as version 1.2. It uses a bottom and cover on top of the FSR to distribute the force equally. However, in this case the bottom and cover parts are shaped as half a capsule to have a better fit inside the capsule shaped stress-ball.

After initial testing we found the following results:

- The use of the capsule shape does work a little better than the sphere shape when it comes to a natural perpendicular distribution of force. However, participants who tested the device still automatically squeeze the ball which leads to strange inputs on the FSR.
- This stress-ball does not use the proper power-sphere grip.
- Healthy participants can quite easily change their grasp to accommodate for the required perpendicular force on the FSR. When tested with ICU patients they had more trouble with distributing their force correctly and automatically squeezed the entire stress-ball.

Figure 39 shows the entire analysis of stress ball version 1.3.



Strengths
- Easy concept
- Distribution of power on FSR is better than in version 1.1
- No more preload on the FSR

Weaknesses
- FSR only measures perpendicular force
- Concept does not make use of power-sphere grasp

Opportunities
- Works for healthy adults
- No preload makes it usable for the game

Threats
- ICU patients have a hard time delivering the force correctly
- The desired grasp form does not deliver the required result
- Inferior concept to that of the grip trainer

Description

Version 1.3 uses the same working mechanism as version 1.2, but instead of a sphere a capsular shape stress-ball is used. This version is mostly made to see if the FSR can be a useful sensor for these type of measurements. The capsular shape does not allow for a good power-sphere grasp.

Findings

- The disks help to distribute the power equally
- The openings made in the ball make sure there is no preload on the FSR
- The capsular shape does not allow for the desired power-sphere grasp.
- The design is better usable than the spherical designs, but utilizes the wrong grasp.

Lessons

- The FSR is somewhat usable in this design, however the power-sphere grasp is then not utilized. As this concept is not usable for the power sphere grasp and the concept works inferior to that of the earlier developed grip trainer, the stress-ball concept with the FSR will be discarded.

Figure 39: Analysis stress-ball version 1.3

5.10 Game testing

Some problems with the game used were clearly visible on the first few sessions.

- The different input needed for the different floors within the game were sometimes hard to control. The difference in input force needed between the first and the second floor was very small which made it hard to precisely control the elevators.
- The characters in the game appeared outside of the screen. The first elevator has to be back into it's starting position for the characters to appear. For the patients it was hard to recognise that there would be no characters available until the elevator was back to it's starting position, so they would often not automatically fully release their grip on their left hand.
- Because of the lack of vocal feedback from the game, it was easy to loose attention. This was possibly the reason that the game was a bit boring and patients quickly lost their interest.

For counteracting the problems that were perceived in the first tests that were done, some changes had to be made. Some problems, such as the input force needed for reaching different floors, could be adjusted instantly. Others, like the lack of vocal feedback, took some more time and help from professional game designers.
By adjusting the required force to get to a certain floor in the game, it was made easier for the participants to control the elevator. To get to the right values took some trial and error, but eventually a version was created that worked well.
As the first test were done with version 3.11, the force exerted on the device was the same as the force exerted on the FSR. By utilizing later versions with multiple springs, the force exerted on the device was 3 times the force exerted on the FSR (see 23b. As the force exerted on the device is linear to the compression of the springs, it is also linear to the displacement of the handle. With 3 springs the displacement of the handle needs to be larger for the same amount of input on the FSR, which means the sensitivity of the controller is lower. This leads to a system that is easier to control.

The problems that were noted in the game were a bit harder to adjust. The video game was one borrowed from SilverFit and making changes to the layout and sound had to be done by one of their professional game designers.

6 Discussion of results

The goal of this design study was to create a device that allows ICU patients to play video games that help them in their physical and mental well-being. We meant to create a device that helps with muscle weakness and is therefor beneficial for the quality of life after ICU discharge, but can at the same time take the attention away from the critical illness and the ICU surroundings.
For this we developed a design that can help in strengthening the patients' hands and lower arms, which in term can lead to an improved quality of life after discharge. Next to that, we chose to use a video game that can be enjoyable for the patients, so that it can take the attention away from the stressful ICU surroundings. Also, the cognitive effort needed for successfully playing the game can be beneficial to the patients' cognitive functioning, which in term can help prevent delirium.

List of requirements

In section 4.12 a list of requirements has been formed to be used as a guideline throughout the study. Preferably all of the requirements stated in this list would be included in the final design, but by using the MoSCoW method, a distinction has been created between the most and least important features. From the entire list the following features are included in the final design:

✓Grip force control that detects multiple ranges
-*Established by using FSR to detect the force exerted on the device*
✓Be usable for patients with MRC4- or higher
-*Established by making use of different springs and spring configurations*
✓Be understandable for patients that are moderately to fully cooperative
-*Established by using a simple game and making use of recognisable motions*
✓No design features that may cause safety risks for the patient
-*Established by smoothing all the edges of the design, making the device disposable and adding extra precautions to the game setup*
✓Must work in the setting of an ICU room
-*Established by creating a device that does not interfere with any other machine that may be present in the ICU room and making use of a mobile stand with the monitor and pc connected to it*
✓Design that eliminates chance of patient to patient cross contamination
-*Established by creating a device that is disposable for all parts that contact the patient.*
✓Big enough monitor for easy visibility
-*Established by using a mobile monitor with a 75cm screen*
✓Patient specific resistance setup
-*Established by making the device work with different springs and by the easily adjustable settings menu in the game*
✓Easy to fabricate
-*Established by making simple designs suitable for different types of fabrication*

From the most important section, the must have section, 100% score is realized. This is the part that ensures that the final concept works for the intended goal and for the target audience.
From the should have section 60% score is realized. The two features from the should have section that did not make it into the final design were the ability for caregivers to set up the game and working throughout the entire range of motion.
The ability for caregivers to set up the game is, subsequently, something that could be placed in the "could have" section of the MoSCoW method. This feature is something that is of more importance in a later stage of research and what could be added during further development.
Working through the entire range of motion was

External circumstances

As I started my graduation project in the beginning of 2020, I encountered a lot of difficulties due to COVID-19. Just after I joined Ben van der Hoven, intensivist in the EMC, for a few days to experience the day-to-day action on the ICU, the country went in lockdown. This meant that for several months I was unable to follow the planning I intended to.
First of all, the EMC Rotterdam closed their doors for anyone who had no specific reason being there, which included all the students. SilverFit also closed their doors during this time and so did the TU Delft. This all happened in the beginning of March and the EMC Rotterdam did not reopen their doors until the second week of June. This meant that over 3 months I could not get any testing done when I really wanted to. Also, because the TU Delft was closed for a long time, I could not get any 3D printing started. Luckily the faculty of industrial design reopened their doors for graduation students after a while, which meant that, with a little help getting me access to the industrial design engineering faculty, progress could be made again.
The time during the corona lockdown of the Netherlands was mostly spent with doing research on ICU patients, possible movements and the effects they might have. Also I started with making preliminary concepts to test with the FSRs and Arduino and designing to-be 3D-printed models for when the lock-down would again be lifted.
Besides the limits the lockdown put on my progress, it also had negative effects on my personal well-being. Life changed as social life came to a hold, visiting family and friends was out of the picture, gyms were all closed and everyone was living in their own small bubble. I noticed through these months that I did not cope with this in the best way; a lack of structure, physical activity and social events did not work wonders for my mental health.

Target audience and protocols

The scope of our research has been on patients with MRC4- or higher. A big part of the ICU does however have a lower MRC score. The physiotherapists would love to have a device that also includes patients with an MRC of 1, 2 or 3 to practice with. There are multiple reasons that this patient group was not put in the target audience of our research, the most important being that designing for patients not being able to use their power against resistance would make for difficult force measuring. These types of measuring on their own would not have been the problem, however testing with these types of sensors would have been a lot harder. The protocols that have to be followed for testing with for instance electromyograms (EMGs) are complex and take up a lot of time. The corona pandemic drastically shortened the time frame for practicing, but also had most of the ICU staff busy with other things than my study for a long time. This meant that during this time there was no way of getting any protocols approved. For this reason I decided to focus on a target audience for which the chance of practicing my device would be more feasible.

3D printing

During this study a lot of designed concepts have been fabricated using 3D printers. The 3D printers at the faculty of industrial design engineering at the TU Delft were at our disposal. These 3D printers are all of the type Ultramaker 2+, which are material extrusion printers. The material used for these 3D printers is PLA, which is a fairly soft type of plastic. The dynamic friction properties of 3D printed PLA are dependent on a number of varieties including material quality, surface finish, temperature and direction of printing. For these reasons (without testing) it is hard to give an actual value to the dynamic friction coefficient of the printed material.
There are however some things that may improve the friction properties of the models. The first thing is the material, it is known that at low temperatures and low speed the dynamic friction coefficient of nylon is a lot better than that of PLA (when all other variables are the same). Therefor replacing PLA with nylon might be a step in the right direction.

Another solution that, in combination with changing the material, can make a big difference, is to use a different fabrication method. Material extrusion is not the most accurate form of 3D printing, but it is very suitable to quickly make moderately accurate and cheap prototypes. It does however leave quite a lot of surface unevenness. Material jetting of nylon or other hard plastic parts would be a better solution. Material jetting can produce smooth parts with surfaces comparable to injection molding and very high dimensional accuracy. The downsides to material jetting are however that it is a more expensive technique than material extrusion and the created parts are more susceptible to breaking during use because they are less flexible than parts made with material extrusion.

Game shortcomings

During the initial testing with ICU patients we noted that the patients did not instinctively return the left elevator to the starting position, but instead kept some pressure on the device. Because of this small amount of pressure the elevator stayed at the "yellow" floor, and no new characters arrived on the top platform. Because there were no characters at the top platform the patients were not encouraged to return the elevator to the top floor. A solution to this problem would be to have the characters spawn in view at the top platform. This way the patients are reminded that there are new characters waiting to enter the game.
The original SilverFit game did not involve any sound in the game. It has been proven that sound feedback has positive effects on the game, but as SilverFit never officially released this game they had not gotten around to creating sounds for it. Healthy participants noted that the lack of sound quickly makes the game dull. The same experience was noted during testing with ICU patients. As there is no form of vocal feedback when the characters arrive or leave the game, it appears that the patients get bored rather quickly.
For this reason sounds were developed to be put in the game. After consulting with an expert in sound design, the decision was made to use bell sounds. The idea was to put the sounds in the game for all events that changed the status of the characters. This meant that a sound is played every time a character arrives in the game, every time a character reaches the right floor and every time a character successfully finishes the game. However, due to technical difficulties the final version of the game in which the sounds were implemented was not ready for testing before finishing this paper.

Another thing noted during testing with ICU patients was that the patient feedback varied a lot. A number of older patients told us that they were not really interested in playing video games. This could be because of this particular game, or because they are just no fans of video games. Other patients noted that they thought the game was boring and did not inspire them to keep playing for a long time. Luckily there were also patients, who were usually younger than the median age, who said that they did like the game.
With so many different patients that all seem to enjoy different things, creating one single game that will be the most fun for everyone is near impossible. For future work there might be a bigger collection of games available.

Stress-ball difficulties

The use of stress-balls is nothing unusual on the ICU. Physiotherapists often use these to help restore hand functioning in patients throughout the hospital. For this reason we wanted to see if we could simply use an FSR inside one of these foam-rubber stress balls. However, we soon found out that the FSR might not be the right sensor for this device or for the power-sphere grasp.
The power-sphere grasp is based on squeezing a spherical object. When this grasp is used the force on the sphere is exerted in many different directions on the outer shell. Figure 16b shows the grasp and how the fingers are placed all over the sphere. Figure 40 shows how much force each finger exerts on the sphere during this grasp. The FSR that we use to control the game needs a force that is perpendicular to the sensor. Because only a small portion of the total force exerted on the sphere is perpendicular to the FSR, it is very hard to control the game with a combination of the power-sphere grasp and an FSR. The basic working of the stress-ball does however work quite good and patients automatically know how to use it. Another type of sensor, which measures force independent of the direction, could make this design a very good solution.

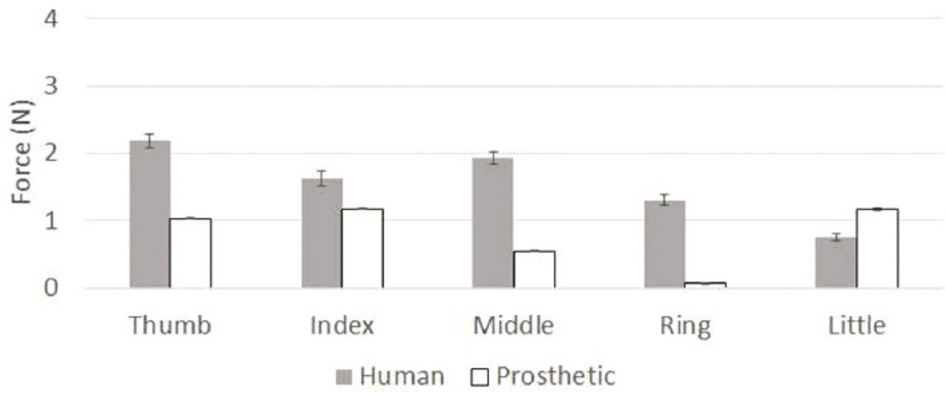


Figure 40: Distribution of power in power-sphere

Safety

A lot of preparations had to take place before we could commence testing with ICU patients. First the study design had to go through protocols to ensure the safety of the exercises and the device. Before testing the appropriate material had to be delivered to the EMC Rotterdam. SilverFit made one of their portable television and computer systems available for testing purposes.
Before this system could be used on the ICU, all of the devices and the construction they were connected to had to go through testing by the technical staff of the ICU. As the design we made uses FSRs, there is a (very small) voltage flowing through these resistors. For safety reasons the whole system therefor had to be disconnected from the regular power grid available in the ICU rooms. To do so an isolation transformer had to be used between the regular power grid and the system used. This isolation transformer makes sure that whenever there would be an earth leak, the system would be cut off from power immediately. This protects the patient safety as it prevents any electrocution hazard from happening.
Next to that, the designed concepts had to ensure that patient safety was always considered. In our designs this was done by making sure that the FSRs were never in direct contact with the patient, all edges of the device were smooth and that there were no parts in which a patient could get their skin stuck. The testing was always done under the supervision of either a ICU physiotherapist or an intensivist, to ensure that the patients were not asked to do any exercise beyond their power.

Iterations

There was some delay between each iteration. After testing the device on the ICU and going over the results, a new design had to be made. This design then had to be 3D printed at the TU Delft, post-processed and reassembled all before being ready for a new round of testing. This process often took up to two or three days. The 3D printing progress is pretty slow and there was a limited timeframe every day in which the 3D printers were available. If everything went well the 3D printed designs could be acquired on the following working day. However, when something goes wrong during the 3D printing process, it often takes hours before this is noticable. So more than one time the 3D printed models had to be redone due to problems with the printer, the design or the material. This delay between iteration and retesting often made for frustrating situations.

Target audience

Even though the device is made for ICU patients, it will probably be useful for many more patients in the hospital. However, as our target audience during this study was ICU patients, we only wanted to do the testing with critically ill patients. For this reason we were very dependent on the ICU population at the times of testing. It happened multiple times that there were no cooperative patients on the ICU or that the cooperative patients were physically or cognitively incapable of using the device.

7 Conclusions

7.1 Main research question

"What are the design characteristics of an interactive video game system to be used in rehabilitation and early mobilisation of ICU patients?"
With the concepts, we want to to create an interactive video game system that could help ICU patients in their physical rehabilitation as well as their mental health. To exert a positive effect on the QOL and ADL of ICU patients after hospital discharge, the focus has been put on training sub-maximal grip force control, utilizing the medium wrap and power-sphere graps 16a 16b. The designs are made using a list of requirements that includes all the must, should, could and would haves (see "Moscow Method", n.d. and section 4.12).
To be able to convert the force exerted in these grasps to a useful input, a design has to be made that is able of translating a force to a useful input for a game. For this an FSR is used, that converts force to changing resistance. This is then registered by an Arduino, which converts the input into a useful output that is used to control the game.

The design for power-sphere grasp is based on a stress-ball and, to create the concepts, existing stress-balls are converted to test feasibility. After three concepts the conclusion was formed that the combination of the stress-ball concept and the FSR do not work. The FSR is only useful for force that is perpendicular to the sensing area. With the power-sphere the force is exerted on the surface area of the stress-ball in multiple directions, which in turn has the effect that the FSR can not register the force as desired. For this reason the power-sphere concept in combination with the FSR is discarded. The power-sphere could well be used with other types of sensors, which will no further be studied in this thesis.

The design for the medium wrap grasp is roughly based on currently existing grip strength trainers. Metal helical coil springs are used to transfer the force exerted on the device to the FSR. The FSR together with the connected Arduino convert this force to the required input for the game. After multiple design revisions we came to the final concept visible in figure 35 & 41. The final concept is designed with 3 cylinders in a row, in which helical coil springs are placed. On the bottom of the middle cylinder there is room to place the FSR that can register the force exerted on the spring. The three springs are compressed by a handle that is attached to cylinders. The cylinders and the beams that hold the cylinders to the handle have an outer diameter close to the inner diameter of the cylinder liners, to minimize the play in the system. By exerting a force on the top of the handle, the springs compress. A force equal to the force on the middle spring is then exerted on the FSR.
Figure 41 shows us the Front, side, top and bottom view of the final concept.

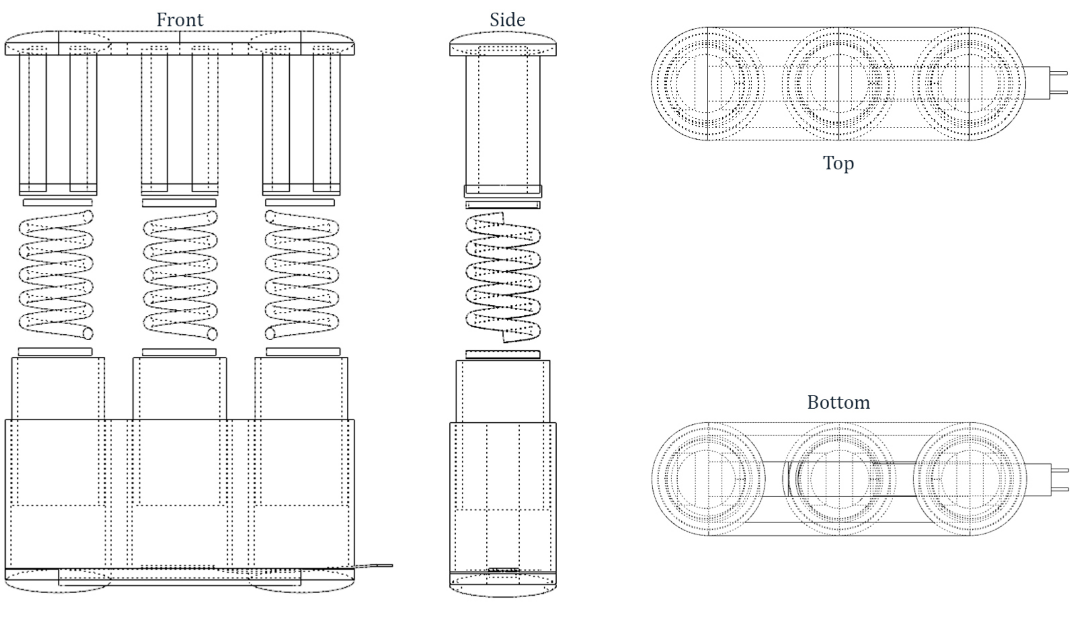


Figure 41: Final grip trainer concept

7.2 Discover

"What are the problems that occur during ICU stay?"
The effects of ICU stay can be detrimental for the patient's entire life. Not only does the reason for admission to the ICU often have lasting effects, but staying in the ICU can have detrimental effects on it's own as well. Because of physical and mental problems left from ICU stay, returning to their own home, job or hobbies after discharge are often not certainties. 30 to 80% of ICU patients develop PICS during their ICU stay and over 50% of ICU patients can not return to their work one year after ICU discharge. A few days in the ICU can lead to months or even years of recovery, with PICS causing major problems in both physical as well as cognitive abilities.

"What is known about the effects of early mobilisation and video gaming as rehabilitation?"
The studies on early mobilisation have become even more relevant in the last months as the hospitals have been flooded with Covid patients. The effects of early mobilisation on patient recovery have proven to be positive. Most studies show increases in exercise time, MRC-SS scores, physical performance and stability. Early mobilisation is safe and patient specific early mobilisation should be considered as soon in the treatment as possible. Current commercially available interactive gaming devices show to improve patient physical and cognitive functioning in different parts of rehabilitation. Different studies show that gaming as an addition to the regular rehabilitation improves balance, grip strength, functioning in ADL and general motor function. They also show the motivational benefits of using gaming, as patients seem to enjoy exercising more when it's incorporated in an interactive game, which in term relates to better adherence to the therapy.

"In what way can video games play a role as an addition to current physical therapy?"
Because the effects of interactive gaming have shown to benefit patients' physical performance and adherence to therapy, gaming could very well be incorporated in current physiotherapy protocols. As early mobilisation has proven to be a safe method for rehabilitation on the ICU and research has shown that video games in rehabilitation usually do not add any safety concerns, the use of interactive gaming as an addition to conventional therapy in early mobilisation of ICU patients seems to be a promising new form of therapy to explore. It should be used as an addition next to regular forms of physiotherapy and in this way it might stimulate the patient to exercise and adhere in their rehabilitation therapy.

"What new insights can be gained from the care-giving staff on the ICU?"
Different types of commercially available video games have already been tried for ICU patients, but as they are not designed with a critically ill target audience in mind, they show a lot of shortcomings and are often unusable. Care givers would like to have a system that is usable for a large group of critically ill patients on the ICU. It should have an easy interface, so that it can be started up by anyone with only limited preliminary knowledge, to reduce any thresholds for using the game. They would love to have a device that patients can start up themselves or together with their family, to increase the time spent exercising throughout the day.
From the time spent on the ICU during this research, it got clear that the game should be really basic and the movements needed for the input should be easy. Patients on the ICU usually do not have the concentration to play complicated games or play games for an extended period of time. When the game is easy to understand and easy to perform this might increase the utilization.

7.3 Define

"What are the barriers to current rehabilitation techniques?"
Physicians have reported a large variety of different reasons that inhibit rehabilitation. Figure 6 shows the entire list. The most reported barriers are a lack of available nursing time, too much sedation for active mobilisation, physiotherapists have too little time per patient, patient has a delirium that is too invasive or rehabilitation may bring the patient's safety in danger. From our literature study we have however found out that patient safety is in reality a smaller risk than it appears. All studies mentioned in *Table 2* have shown that early mobilisation of ICU patients is safe, as long as patient specific therapy is used.

"In which ways can ICU patients physical and cognitive functioning be scaled?"
There are many different scales to judge an ICU patient's well-being, but most of these scores only focus on a single specific part of patients functioning. The most important scores for this research are based on illness severity, muscle strength, agitation level and level of cooperation. The Apache-II scale analyses the patient's illness severity based on a number of variables, which gives a score from 0 to 71 and can be used as a guideline for different medical interventions, as a red flag for mobilisation but also as an predictive indication for death rate. The MRC-scale gives an indication of the patient's maximum muscle force. It can be judged either per muscle group or as a total score in the form of the MRC-SS, which considers 6 different muscle groups all together. The RASS scale is used to assess a patient's agitation level. It's primary use is to evaluate whether a patient is in need of more or less sedatives. The S5Q score is a standardised series of questions used to judge the patient's cooperation. The total score is equal to the number of tasks successfully fulfilled.

"What is the target audience for which the system will be designed?"
For a well made design it is important to first specify the target audience. The target audience for this project has been chosen in a way that it includes as many patients that are physically and cognitively capable of playing the video game as well as possible. Our target group includes all adult patients from the regular ICU that are awake, cooperative and physically capable of performing simple movements. Patients should have an MRC score of at least 4- and should have no red flags or contraindications against rehabilitation. Patients that -for any reason- are not suitable for mobilisation or rehabilitation are not considered to be in the target audience. Section 3.8 shows all the specifics of this patient group.

"What are the possible movements that can be used as an input for the game?"
The target audience of this research is semi mobile to fully mobile and has an MRC score of at least 4-, but is still bound to their bed or chairs. An MRC score of 4- means that the patient can use their muscles for movements against gravity and against some resistance. For this target audience usually a big variety of motions is usually possible, unless they have specific indications hampering them from certain tasks. Section 3.9 includes the most frequently used part of all possible motions that are currently being used by the physiotherapists for rehabilitation purposes. Section 3.9 narrows this list down and shows the movements that the ICU physiotherapists would like to be included in the final design.

"How is gaming currently utilised for rehabilitation on the ICU?"
Most current mobilisation or rehabilitation games for the ICU are not specifically targeted at ICU patients. Instead, these are regular rehabilitation games that are also being used for patients on the ICU. Consequently, only a small group of physically very capable patients can make use of these games.
One device that is being used for ICU patients that can not be mobilised yet, and so can not leave their bed, is the bedside cycle ergometer. This involves a cycling device that lets the patient move through a virtual environment while they are cycling on the ergometer. The problem with this game is again that it can only be used for patients that are physically capable and have an MRC score of 5, which excludes most of the ICU patients.

7.4 Develop

"What are the design goals for a new way of controlling video games for ICU patients?"
The design goal is to create an interactive video game system that allows patients on the ICU to play a video game that helps them in their mobilisation and rehabilitation. The aim of this video game is that the patient increases muscle force control, enjoys the game-play and has a form of distraction that enables them to keep their mind of their critical illness for a while.

"What exercises should be used as input?"
To make a considerable impact on QOL and the ability to perform ADLs after ICU discharge, practicing grip control in grasping motions has been chosen as input. Multiple studies have shown that training finger movements has a positive effect on sub-maximal grip force and hand control in elderly participants. Because the medium wrap and power-sphere are the most used grasp forms in ADL, these grasps will be the base for the design. It has also been shown that the use of sub-maximal grip force control is the most usable for practicing in ADL. Maximum grip strength is rarely used during ADL and is therefor of lesser interest.
Two different types of grasps, the medium wrap and the power-sphere, have been chosen as the required movements to use as input for the final designs.

"Which system solutions can be defined to translate the input from the exercise to the game?"
Grip control is based on the ability to control the fingers through their entire functional range of motion. Because we want to have the participants train for grip control through their entire ROM, we need a system that can translate this ROM into a useful output of the game. For this we created table 3, which shows the most suitable sensors. Figure 17 shows a weighted table used for determining that the FSR would most likely be the best sensor for our purposes. The FSR can be used to determine the total force exerted by the patient, which in turn can be used to establish the input to the game.

"What are the essential requirements that should be present in the final solutions?"
Because of the established target audience it is important that the game is usable and understandable for patients that are moderately to fully cooperative and have an MRC score of 4 or higher. As grip force control is chosen as the final input, the device should be able to distinguish at least a few different ranges of force. The final design can not have any features that may harm the patient in any way and it should not interfere with any of the equipment and machines connected to the patient for recovery purposes. Also, because of the vulnerable patient group, the design should make sure that risk of cross contamination is kept to an absolute minimum.

"What game solutions can be used for the chosen input form?"
The scope of this research was not to design the game itself, so we decided to look for an already existing game from SilverFit. A range of games from SilverFit was scanned looking for games that would be usable for our purpose. Because we want to train both the left and right hand simultaneously, the ideal game would have two different required inputs. Also, because we want to train grip force control through the entire ROM and not only maximum grip force, we wanted a game that would use more input than just a positive or a negative. Next to that, the game should be easy to understand for our target group. The best solution was found in the elevator game (see 45). This game needs two different inputs that can distinguish 4 different levels of force.

7.5 Deliver

"What are the required specifications of the final versions?"
The final design needs to be usable for patients with MRC4- or higher, that are moderately to fully cooperative and should be usable for patients that are not yet capable of being mobilised. It should use grip force control through the active ROM of the hand as input and should be usable in the ICU room setting. The design may not have any features which may cause any safety effects for the patient in any way and should be designed to eliminate chances of patient to patient cross contamination. There will be two different concepts, one of which utilizes the medium grasp as required movement, the other one utilizes the power-sphere grasp as required movement. Each of the designs should be designed to work for the largest part of the target audience and the designs should allow for easy modification to be suitable for different hand sizes.

"What methods can be used to assess the concepts?"
For assessing the design qualities, a number of trials are done before testing with actual patients is done. The first assessment of the design is by personally testing the device to check for any fabrication or design errors. The model is checked for any properties that may disqualify it as usable for ICU patients, any faults in the mechanism or in the working and for design choices that may possibly cause problems in the future. If the design is approved, the next step will be testing the design with healthy participants to get more objective feedback. From there the decision is made whether or not the design will be tested with critically ill patients or that it will be discarded and replaced by a new version.
If the decision is made to test the design with ICU patients, the rest of the assessment will be based on two factors. The first is observed patient performance; this is to see if there are any inconsistencies in the use of the concept and to see how the patients manage to play the game. The second part is based on small questionnaires with the patients; the patients are asked for their opinion on the design, the difficulty in use and the game.

"How will these assessments affect new design alternatives?"
The assessment of the design concepts leads to iteration steps. After each design an assessment is done by a SWOT analysis. This creates a list with points of weaknesses but also strengths and opportunities. After this SWOT analysis either an adaptation to the design is made, or the design is scrapped and a new design is started from scratch. This iteration process is repeated until the desired design is met.
Besides the iteration steps for the concepts, the assessment also showed the shortcomings of the game. From those shortcomings the game was changed on multiple points to be used for further testing.

"What is the proposed final design comprised of?"
Multiple iteration steps have led up to the final design, which can be seen in figure 35. The design is based on the medium grasp and uses an FSR to calculate the force exerted and translates this to a useful input to control the game with. The concept uses 3 metal coil springs in a row, which can be changed according to the participant's grip strength. The concept is designed in such a way that possible jamming of the device is kept to a minimum. All edges of the design are smoothed out to minimize safety effects en maximize user comfort. The concept is designed to be disposable so that patient to patient cross contamination is kept to a minimum.

8 Evolve

8.1 Achievements

The most prominent achievement of this study is the fact that we managed to create and test functioning new designs within the given time frame and with all the extra barriers provided by Covid-19. There is a working system with different controlling mechanisms that could, when fine-tuned and after clinical testing, be put into production. This is, to my knowledge, the first interactive video gaming device that is designed specifically to be used in rehabilitation of immobile ICU patients. Earlier studies were all done using commercially available gaming devices or were focused on more mobile patients. The subject of interactive video gaming for immobile subjects was still largely unexplored. I believe that with this study we have made the first steps into creating devices specifically for bed-ridden ICU patients.
As there is a new study being started from October 2020 by SilverFit and the EMC Rotterdam, they will continue with the progress and results from this study, and hopefully our designs will at some point be used on different ICUs.

Testing the designs on the ICU of the EMC Rotterdam has lead to numerous new insights on both the device as well as the game itself. It provided us with useful ideas that were used in the iteration steps and eventually delivered new concepts. Being able of testing with the actual target audience made testing the feasibility a lot more useful. Design shortcomings that seemed to be minor flaws during preliminary testing, turned out to be major flaws during testing with patients. For instance the play in grip trainer version 3.11 did not seem a big problem when testing with healthy participants, but made the device very hard to use for critically ill patients. If it had not been for the ability to test with the actual target group on the ICU, these flaws could possibly have made it into the final design.

Because of Covid-19 and the amount of people that has been admitted to several ICUs all around the world, our subject has become even more relevant. For the last few months there have been several thousand more ICU admissions than usual. A lot of these patients will have the same problems with their physical and cognitive functioning after the ICU as regular ICU patients have. A device like the one we designed might have been a very welcome addition for the patients to help them during their ICU stay. Distraction from the stressful ICU environment can have beneficial effects on reducing and preventing delirium, which in term helps prevent PICS.

There is still a big part left to discover after this study. We have only focused on one single type of movement when there are so many more to study in the future. With constantly evolving technologies, there is a good opportunity to use wireless devices to track the movements in the near future. I think that the right implementation of a wireless Inertial Measurement Unit (IMU) can be very helpful in tracking multiple movements.

8.2 Future work

As the scope of this paper was to explore the possibilities and feasibility of interactive video gaming for rehabilitation on the ICU, there is lots of room for further expansion. Next to that, there is a good opportunity to continue with the created designs and do scientific research on the effects they can have on ICU patients.

Because of the target audience that excludes patients with an MRC score of 3 or lower, a big part of the ICU patients is not able of using the design. The target audience formulated in this research has been guided by a limited time frame. For future research it would be desired to expand this target audience to include patients that have an MRC score of 3, 2 or 1. This could be done by using, for instance, EMGs or wireless sensors that can be used without resistance.

The focus of this thesis has been put primarily on improving grip force control. The final designs have then been designed with grasp as the desired input and these devices are only meant for exercising hand and forearm muscles. There is a big range of possible other movements that can be used as input for gaming. All movements from section 3.9 could possibly be used for future games. New mechanisms for translating these movements to input should be made in order to utilize these for video games. For many of these other movements other sensors should be used. Future studies could and should focus on utilizing a larger number of these movements. Movements that require limb movement throughout a larger range of motion, could possibly be measured using IMUs. At the start of this study I already tested a couple of IMUs for possible inclusion in my design. However, as grip force control was chosen as the required input for the game, IMUs were of little use for this study.

During testing we noted that every patient has something different they would like to see in a video game. For future continuation of this project it would therefor be a good idea to include a variety of different types of games. Some of these games could be more targeted to the actual playing part and could possibly be 2D arcade games, while other games might be more focused on cognitive stimulation and use puzzles or quizzes that patient have to solve. A bigger variety in games can accommodate to a larger group of patients and can increase adherence.

For the stress-ball concepts we found out that the FSR is probably not the best usable sensor. The FSR can only register force that is perpendicular to it's service, with a stress-ball the force is usually not delivered perpendicular but instead the force is distributed all over the surface of the sphere. For the stress-ball some kind of pressure sensor would probably be a better solution. Another option that might be worth looking into in the future is the use of some sort of rubber balloon in which a pressure sensor is placed instead of the FSR. When squeezed the air pressure inside the balloon will rise, the pressure sensor can register this and this can be used as the input for the game.

For future research it will be well worth looking into the use of VR systems. The use of VR goggles has been an upcoming topic for the last years and it has proven to be effective for minimizing trauma for ICU patients. For this research we have chosen not to use VR goggles for a number of reasons, one of which being that due to Covid-19 the time we had to practice on the ICU was shortened drastically. Testing VR goggles on patients needs a lot of preliminary conditions and testing of the device, which would have reduced the testing time to an absolute minimum, if any.

As SilverFit, together with the Erasmus MC, are continuing the project under the name IC-Move, there will luckily be a sequel to my work. The IC-Move project has received a Eurostars funding, which makes it possible to study interactive video games for early mobilisation on the ICU for 2 more years.

Appendices

Appendix 1: Gelre hospital observations

Impressions and knowledge gained at the Gelre hospital

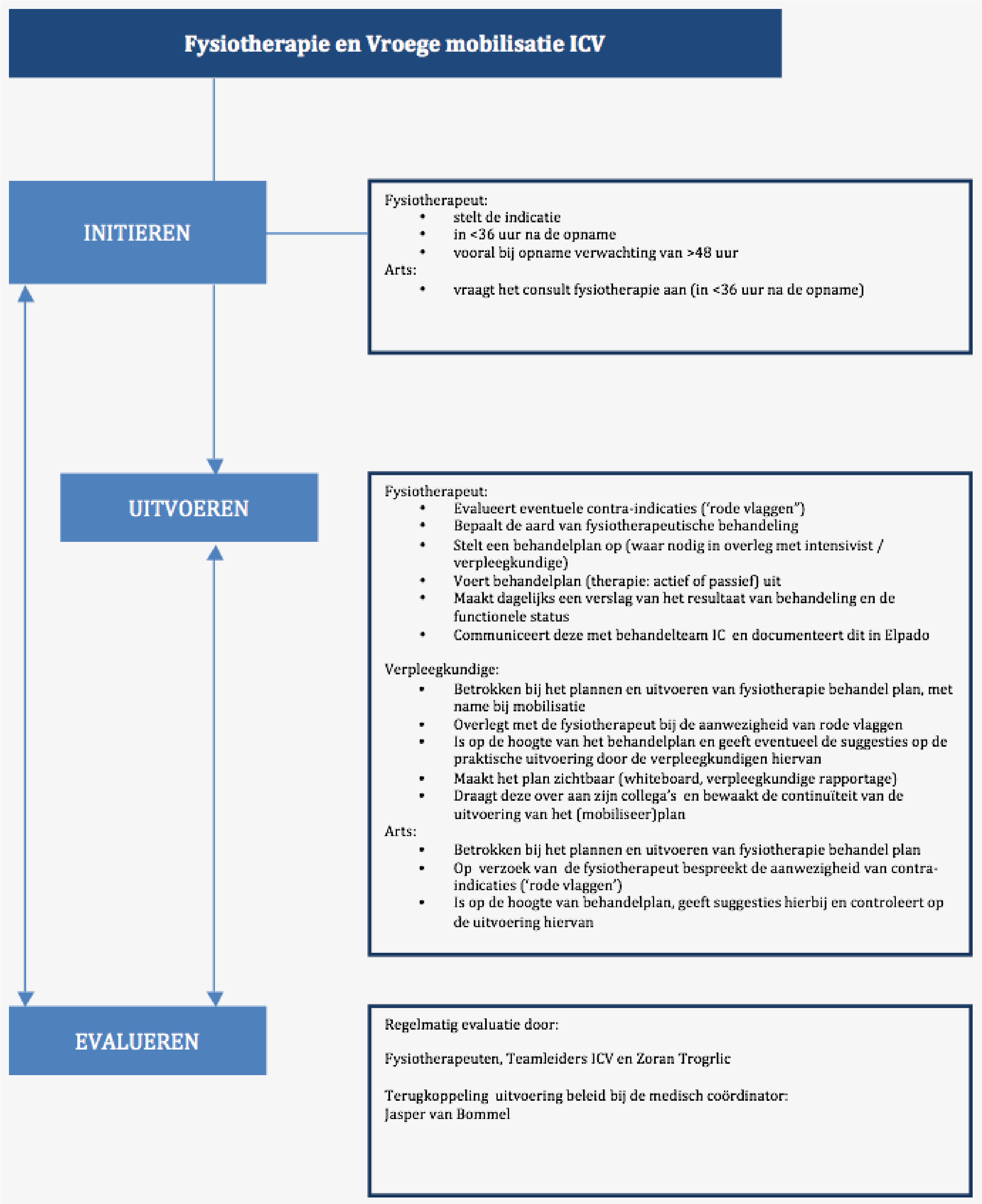
- To get patients to exercise in a fun way, the ICU staff has tried to use a Nintendo Wii. Problems with this are however that the use of a Wii controller is quite complex and the movements required are too hard and too quick for their patients. Movements often involve simultaneous control of both the displacement of the controller as well as pressing and releasing several buttons. Patients on the ICU are usually cognitively not good enough to control all of these different tasks at the same time while still focusing on a video game. There is only a few patients that can actually use this system, but for most patients it is just too hard.
- While from the first conversations I had with SilverFit, I learned that the ICU staff was looking for ways to make the actual mobilization of patients more enjoyable. So the idea was basically to create a game that patients could play while transitioning from laying to sitting/standing. However, from speaking with the staff at the Gelre hospital, I came to the conclusion that -on the ICU- they were not actually looking for anything that might help them with the transition movements patients make. For all lay to sit, sit to stand etc movements there are so many people involved that they don't feel like any other component might add to the experience of the patient. Besides that, when the patients still need all their concentration on the movement, adding any game components would probably be too much.
- Patients are usually on beds made to reduce pressure sores. These beds work really well for what they are meant for, but the downside is that the beds are really unstable. Sitting up is already a very demanding tasks for most patients and they often have to be supported by one or more caregivers.
- When a patient is being transferred from a bed to a chair this is often done with a lift. Otherwise it takes the support of multiple caregivers to ensure the patient safety in the progress.
- Patients are often too weak (and there are so many tubes wires etc connected to their bodies) to make the transition from laying on their back to laying on their side. So this is also not a good movement to incorporate in a game.
- There is a big group of patients on the ICU that are too sedated to get in contact with. Usually over half of the people on the ICU can not perform any active physical movements. A physiotherapist is needed for the flexion of their joints. So that they can passively exercise. Patients who are too sedated to respond to any stimuli can not take part in any exercising games.
- What I noticed when I saw the physical therapist working with some of the patients that would be "good" enough to play games with, is that they tremble a lot after exercises. For instance when they have to lift their hand, they can usually perform the exercise when the therapists says so, but when they try to relax the muscles, their hand starts shaking.
- Another thing I noticed is that the patients usually are not capable of doing a lot of repetitions (3-5 max) and often they have to get new instructions for the game after 1-3 repetitions.
- Another problem that was noted several times, is that patients often do not have their glasses with them. This problem seems to be more common than you would expect, so if we want to work with a screen where they are playing the game on it has to be very big or placed close to the patient. Something like an apple iPad on the edge of the bed won't work.
- Some of the more usable exercises would be: twisting your wrists, squeezing a ball (very softly as there's usually little power in their hands), lifting lower arm, lifting upper arm, flexion of ankles (usually the ankles seem to swell up a lot)
- Caregivers like to show patients their achievements, especially over a longer period of time. So something that would be good to incorporate in the game is a way to track the patient's progress so that they can see when they score better than previous days and can see how they get stronger/better.

Appendix 2: Erasmus Medical Center Rotterdam observations

Impressions and knowledge gained at the EMC

- The first thing that became clear was that the approach the Erasmus MC took to taking care of critically ill patients was very different to the approach the Gelre hospital took. At the Erasmus MC their seemed to be much more of a "hands-on" approach. From the way they spoke and the things they said, the ICU staff seemed a lot less scared to mobilize patients.
- They are big fans of getting patients out of bed and into the rehabilitation room. The problem is of course that a lot of patients are simply too weak to be mobilised like this and can not leave their bed/room. Hence they want to see a system that can be used for patients that are in bed or in their room.
- Patients that are physically strong enough to be mobilised often still have many tubes and lines connected to their body. These can be from intravenous lines, colostomy bags, mechanical ventilator or many other different items. The problem is that all these devices hamper the patient in their movements. Next to that, the cameras SilverFit usually uses, do not work when a patient has this many devices and lines connected to their body. Another problem was that the ICU chairs, meant to stabilize patient while sitting, are also too invasive for the camera, as the camera can't recognize a person sitting inside it anymore.
- Other shortcomings from the current gaming devices mentioned by the caregivers were that very small movements can not be observed by the systems. Often patients are not capable of moving their limbs in a full range of motion, but only over very small distances. The caregivers would like to see that these smaller movements can also be enough to play games.
- The biggest wish from the ICU staff was to have a system that is so easy to operate that the patient itself could start it up, to practice from their bed. They would like to have a system that the physical therapists controls and sets up up front, but after that can be easily started up by the nursing staff, patient's family or the patient itself. This to lower the threshold for playing as much as possible. This is also to encourage the nursing staff to start playing games with their patients. If both the nursing staff and the patients enjoy the game, the applicability will probably be the highest.
- Many of the patients on the ICU are cognitively and/or physically too weak to exercise. A lot of the patients are completely sedated or have delirium that is so intrusive that they can not respond to the care-giver. For this reason the goal for the device should be to get patients -that are cooperative- to exercise as soon as they can. Make the threshold for exercising low so that the patients that normally would do nothing can play a game.

Appendix 3: Physiotherapy protocol EMC ICU

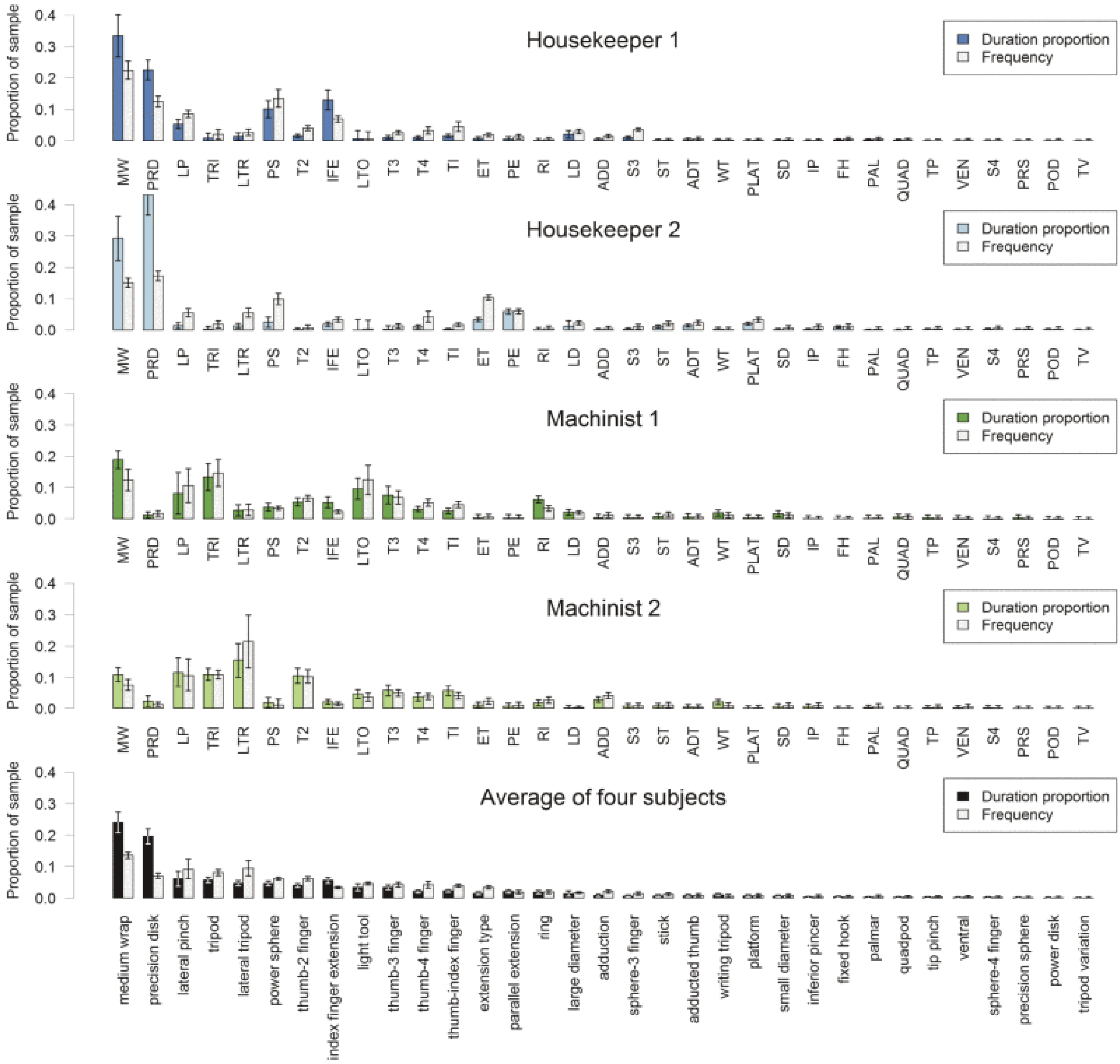


Appendix 4: Activities of daily living

Domestic activities of daily living (DADLs)	
DADL1	Food preparation
DADL2	Housekeeping
DADL3	Laundry
DADL4	Telephone/computer/technology use
DADL5	Office tasks/writing
DADL6	Hobby/sport
Extradomestic activities of daily living (EADLs)	
EADL1	Transportation/driving
EADL2	Shopping
EADL3	Employment-related tasks/tool use
Physical self-maintenance (PSM)	
PSM1	Feeding/medicating
PSM2	Toileting
PSM3	Bathing
PSM4	Dressing
PSM5	Grooming
PSM6	Ambulation/transfer

Appendix 5: Grasp taxonomy, Bullock I.M., 2013

Figure 42: Grasp frequency Bullock I.M., 2013



Appendix 6: Arduino code try out

```
// Define pins:
#define fsrpin A0
#define led1 2
#define led2 3
#define led3 4
#define led4 5
#define led5 6
#define led6 7
// Define variables:
int fsrreading;
void setup() {
  // Begin serial communication at a baud rate of 9600:
  Serial.begin(9600);
  // Set LED pins as output:
  pinMode(led1, OUTPUT);
  pinMode(led2, OUTPUT);
  pinMode(led3, OUTPUT);
  pinMode(led4, OUTPUT);
  pinMode(led5, OUTPUT);
  pinMode(led6, OUTPUT);
}
void loop() {
  // Read the FSR pin and store the output as fsrreading:
  fsrreading = analogRead(fsrpin);
  // Print the fsrreading in the serial monitor:
  Serial.println(fsrreading);
  // Control the LEDs:
  if (fsrreading > 200) {    digitalWrite(led1, HIGH);   }
  else digitalWrite(led1, LOW);
  if (fsrreading > 450) {    digitalWrite(led2, HIGH);   }
  else digitalWrite(led2, LOW);
  if (fsrreading > 550) {    digitalWrite(led3, HIGH);   }
  else digitalWrite(led3, LOW);
  if (fsrreading > 650) {    digitalWrite(led4, HIGH);   }
  else digitalWrite(led4, LOW);
  if (fsrreading > 800) {    digitalWrite(led5, HIGH);}
  else digitalWrite(led5, LOW);
  if (fsrreading > 900) {    digitalWrite(led6, HIGH);}
  else digitalWrite(led6, LOW);}
```

Appendix 7: Arduino code final design

```
#include <TM1637.h>

#include <Arduino.h>
#include <SerialCommands.h>
#include <math.h>
#include "rgb_lcd.h"
#include <string.h>

rgb_lcd lcd;

const int CLK = 3;
const int DIO = 4;
TM1637 tm1637(CLK,DIO);

// Command buffer initialization
char serial_command_buffer_[64];
SerialCommands sCmd(&Serial, serial_command_buffer_, sizeof(serial_command_buffer_), "\r

//---------------------- PIN LIBRARY INITIALIZATION ----------------------------//
String digitalPinIdentifiers[] = {"UNBOUND"/*2*/, "UNBOUND"/*3*/, "UNBOUND"/*4*/,
                      "UNBOUND"/*5*/, "UNBOUND"/*6*/, "UNBOUND"/*7*/
};
String analogPinIdentifiers[] = {"UNBOUND"/*0*/, "UNBOUND"/*1*/, "UNBOUND"/*2*/,"UNBOUND
};
String IC2PinIdentifiers[] = {"UNBOUND"/*0*/, "UNBOUND"/*3*/, "UNBOUND"/*2*/,"UNBOUND"/*
};
int displayValue = 0;
String LCDValue = "";
bool printLCD = false;
//---------------------- PING FOR DEBUGGING ----------------------------//
void pingHandler (SerialCommands* sender)
{
  LCDValue+= "PONG!";
  printLCD = true;
  char *arg;
  arg = sCmd.Next();
  if (arg != NULL)
    sender->GetSerial()->println(arg);
  else  {sender->GetSerial()->println("PONG!");lcd.write("PONG!");}}
//---------------------- BIND PIN TO COMPONENT ----------------------------//
void bindPinToComponentHandler(SerialCommands* _sender){
  // Get the first parameter of the bindPinToComponent call, the pin to bind to
  char* pin_str = _sender->Next();
  if (pin_str == NULL)
  {_sender->GetSerial()->println("ERROR NO_PORT"); return;}
   int pin = atoi(pin_str);
 // Get the identifier to send with the write to serialport
  char* componentIdentifier_str = _sender->Next();
   if (componentIdentifier_str == NULL)
  {
    _sender->GetSerial()->println("ERROR NO_IDENTIFIER");
    return;
  }

  String comp;
  comp = componentIdentifier_str;
```

```
  int pinTranslated = 0;
  // 7 digital 4 analog 4 ICS
  if(pin >= 2 && pin <= 7)
  {
    pinTranslated = pin-2;
    digitalPinIdentifiers[pin-2] = comp;
    LCDValue += " Bound -" + comp + "- pin: " + pin + " ";
    printLCD = true;
  }
  else if(pin >= 8 && pin <= 11)
  {
    pinTranslated = pin-8;
    analogPinIdentifiers[pin-8] = comp;
    LCDValue += " Bound -" + comp + "- pin: " + pin + " ";
    printLCD = true;}
  else if(pin >= 12  && pin <= 15)
  {     pinTranslated = pin-12;
    IC2PinIdentifiers[pin-12] = comp;
    LCDValue += " Bound -" + comp + "- pin: " + pin + " ";
    printLCD = true;   }
  char* pin_mode_str = _sender->Next();
  if (pin_mode_str == NULL)
  {     _sender->GetSerial()->println("ERROR NO_PINMODE");}
 int pin_mode = atoi(pin_mode_str);
   if(pin_mode == "INPUT"){     pinMode(pinTranslated, INPUT);
  }else if(pin_mode == "OUTPUT"){     pinMode(pinTranslated, OUTPUT);}}
void types(String a){Serial.println("it's a String");}
void types(int a)   {Serial.println("it's an int");}
void types(char* a) {Serial.println("it's a char*");}
void types(float a) {Serial.println("it's a float");}
//------------------- UNBIND PIN FROM COMPONENT ------------------------//
void unBindPinFromComponentHandler(SerialCommands* _sender){
  // Get the first parameter of the bindPinToComponent call, the pin to bind to
  char* pin_str = _sender->Next();
  if (pin_str == NULL)
  {     _sender->GetSerial()->println("ERROR NO_PORT");
    return;  }
   int pin = atoi(pin_str);
 // Get the identifier to send with the write to serialport
  char* componentIdentifier_str = _sender->Next();
   if (componentIdentifier_str == NULL)
  {     _sender->GetSerial()->println("ERROR NO_IDENTIFIER");
    return;  }

  String comp;
  comp = componentIdentifier_str;
  LCDValue += " Bound -" + comp + "- pin: " + pin + " ";
  printLCD = true;
   // 7 digital 4 analog 4 ICS
  if(pin >= 2 && pin <= 7){
    if(digitalPinIdentifiers[pin-2] == comp){
      digitalPinIdentifiers[pin-2] = "UNBOUND";
      Serial.println("INCOMING DIGITAL PIN");
    }
  }else if(pin >= 8 && pin <= 11){
    if(analogPinIdentifiers[pin-8] == comp){
      analogPinIdentifiers[pin-8] = "UNBOUND";
```

```
      Serial.println("INCOMING ANALOG PIN");      }
  }else if(pin >= 12 && pin <= 15){
    if(IC2PinIdentifiers[pin-12] == comp){
      IC2PinIdentifiers[pin-12] = "UNBOUND";
      Serial.println("INCOMING IC2 PIN");     }   }
  Serial.println("UNBOUND PORT");
  Serial.println(pin);
  Serial.println("FROM COMPONENT");
  Serial.println(comp);}
void breakConnectionHandler(){}
void breakConnectionAndResetHandler(SerialCommands* _sender){
    displayValue = 0;    for(int i=0; i<=5;i++){
      digitalPinIdentifiers[i] = "UNBOUND";
      delay(10);      }
       for(int i=0; i<=3;i++){
      analogPinIdentifiers[i] = "UNBOUND";
      delay(10);      }
     for(int i=0; i<=3;i++){
      IC2PinIdentifiers[i] = "UNBOUND";
      delay(10);
    }
    LCDValue = " Unbound components ";}
void digitalDisplayWriteHandler(SerialCommands* _sender)
{  char* displayValue_str = _sender->Next();
  if (displayValue_str == NULL)
  {     _sender->GetSerial()->println("ERROR NO_DISPLAYVALUE");
    return;  }
   displayValue = atoi(displayValue_str);}
void LCDWriteHandler(SerialCommands* _sender)
{
  char* LCDValue_str = _sender->Next();
  if (LCDValue_str == NULL)
  {     _sender->GetSerial()->println("ERROR NO_LCDVALUE");
    return;  }
   LCDValue = LCDValue_str;
  printLCD = true;}
//------------------ COMMANDS ------------------------//
SerialCommand cmd_Ping("PING", pingHandler);
SerialCommand cmd_BindPinToComponent("B", bindPinToComponentHandler);
SerialCommand cmd_UnBindPinFromComponent("UB", unBindPinFromComponentHandler);
SerialCommand cmd_BreakConnection("BC", breakConnectionHandler);
SerialCommand cmd_BreakConnectionAndReset("BCR", breakConnectionAndResetHandler);
SerialCommand cmd_DigitalDisplayWrite("DISW", digitalDisplayWriteHandler);
SerialCommand cmd_LCDWrite("LCDW", LCDWriteHandler);
//------------------- SETUP -----------------------//
void setup() {
  tm1637.init();
  tm1637.set(BRIGHT_TYPICAL);//BRIGHT_TYPICAL = 2,BRIGHT_DARKEST = 0,BRIGHTEST = 7;
  LCDValue = " ";
  for(int i=0; i<16; i++){
    if(i< LCDValue.length()){
      LCDValue[i] = " ";      }   }
   // Setup LCD's number of coloms and rows:
  lcd.begin(16, 2);
  lcd.setCursor(0, 1);
  lcd.print(LCDValue);
  printLCD = false;
  for(int i=0; i<=5;i++){
```

```
      digitalPinIdentifiers[i] = "UNBOUND";
      delay(10);   }
   for(int i=0; i<=3;i++){
      analogPinIdentifiers[i] = "UNBOUND";
      delay(10);   }
   for(int i=0; i<=3;i++){
      IC2PinIdentifiers[i] = "UNBOUND";
      delay(10);   }
   // Initialize serial communications:
   Serial.begin(9600);
   while (!Serial);
   //sCmd.AddCommand(&cmd_set_pin_mode_);
   sCmd.AddCommand(&cmd_Ping);
   sCmd.AddCommand(&cmd_BindPinToComponent);
   sCmd.AddCommand(&cmd_UnBindPinFromComponent);
   sCmd.AddCommand(&cmd_BreakConnection);
   sCmd.AddCommand(&cmd_BreakConnectionAndReset);
   sCmd.AddCommand(&cmd_DigitalDisplayWrite);
   sCmd.AddCommand(&cmd_LCDWrite);
   sCmd.SetDefaultHandler(&cmd_unrecognized);}
void cmd_unrecognized(SerialCommands* sender, const char* cmd)
{  sender->GetSerial()->print("ERROR: Unrecognized command [");
   sender->GetSerial()->print(cmd);
   sender->GetSerial()->println("]");}
void loop() {
/*
if(digitalRead(2) == 1){
   //displayValue += 1;
   displayValue = 2;}
if(digitalRead(6) == 1){
   //displayValue += 10;
   displayValue = 6;}
if(digitalRead(7) == 1){
   //displayValue += 2;
   displayValue = 7;}
if(digitalRead(8) == 1){
   //displayValue += 20;
   displayValue = 8;}
*/
//---------------------------------------------- READ ALL AVAILABLE SERIAL COMMANDS COMING IN FROM THE PORT
   if (Serial.available())
      {
         // wait a bit for the entire message to arrive
         delay(100);
         // clear the screen
         if (Serial.available() > 0)
           sCmd.ReadSerial();
      }
//------------------------------------------------------------------------------------------ END ----------------------------------------------

//------------------------------------------------------ WRITE ALL BOUND PINS TO THEIR SUBSCRIBED COMPONENTS -

//-------------------------------------------- DIGITAL PINS
   String seperator = " ";
   for(int i=0; i<=5;i++){
      if(digitalPinIdentifiers[i].equals("UNBOUND") == false){
         int value = digitalRead(i+2);
```

```
      int num = i;
      String id = digitalPinIdentifiers[i];
      String type = "DR ";
      String printString = type + num + seperator + id + seperator + value;
      Serial.println(printString);
    }
    delay(10);
  }
//------------------------------- ANALOG PINS
  for(int i=0; i<=3;i++){
    if(analogPinIdentifiers[i].equals("UNBOUND") == false){
      int value = AnalogRead(i);
      int num = i;
      String id = analogPinIdentifiers[i];
      String type = "AR ";
      String printString = type + num + seperator + id + seperator + value;
      Serial.println(printString);
    }
    delay(10);
  }
//------------------------------- IC2 PINS
  for(int i=0; i<=3;i++){
    if(IC2PinIdentifiers[i].equals("UNBOUND") == false){
      int num = i;
      String id = IC2PinIdentifiers[i];
      String type = "IC2R ";
      String printString = type + num + seperator + id;
      Serial.println(printString);
    }
    delay(10);
  }
//-----------------------------------------------------------------------------------------------

  // LCD RGB Backlit
  // Autoscroll
  if(printLCD == true){
    lcd.setCursor(0, 1);
    String printString = "";
    for(int i=0; i<16; i++){
      if(i< LCDValue.length()){
        printString += LCDValue[i];
      }else{
        printString += " ";
      }
    }
    lcd.print(printString);
    delay(10);
    LCDValue.remove(0,1);
    if(LCDValue.length() == 0){
      printLCD = false;
      lcd.setCursor(0, 1);
      delay(10);
      lcd.print(" ");
    }
  }

  // Digital Display
  tm1637.display(displayValue);
```

```
}

int AnalogRead(int _index){
  int returnValue = 0;
  switch(_index){
    case 0:
        returnValue = analogRead(A0);
      break;
    case 1:
        returnValue = analogRead(A1);
      break;
    case 2:
        returnValue = analogRead(A2);
      break;
    case 3:
        returnValue = analogRead(A3);
      break;
  }
  return returnValue;
}

void arg (const char *command)
{
  // Error handling
}
```

Appendix 8: Red flags for mobilisation

Red flags for mobilisation

- Heart functioning
  - Recent myocardial ischaemia
  - Heart rate < 40 or > 130
- Blood pressure
  - Map < 60mmHg or > 110 mmHg
- oxygen saturation

– $\leq 90\%$

- Ventilation parameters
  - FiO2 > 0.6
  - PEEP > 10cm H2O
- Respiratory rate
  - Respiratory rate > 40 p/min
- RASS score
  - RASS score -5, -4, 3 or 4
- Heart failure medication
  - Dopamine > 10 mcg/kg/min
  - Nor/adrenaline > 1 mcg/kg/min
- Body temperature
  - > 38.5 degrees Celsius
  - < 36 degrees Celsius
- Other red flags
  - Abnormal sweating
  - Abnormal facial colour
  - Pain
  - Fatigue
  - Surgical counter indications
  - Invasive lines that seriously hamper mobilisation
  - Neurological instability: ICP > 20 cm H2O

Appendix 9: Visualisation of the game

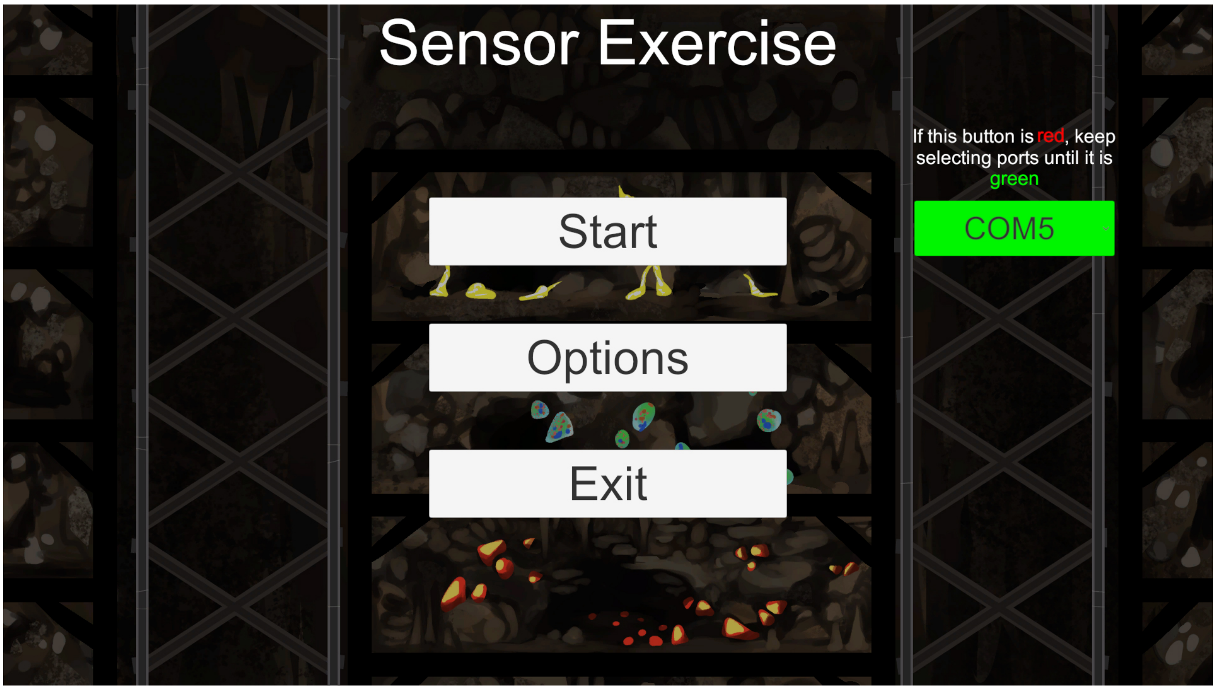


Figure 43: Game homescreen

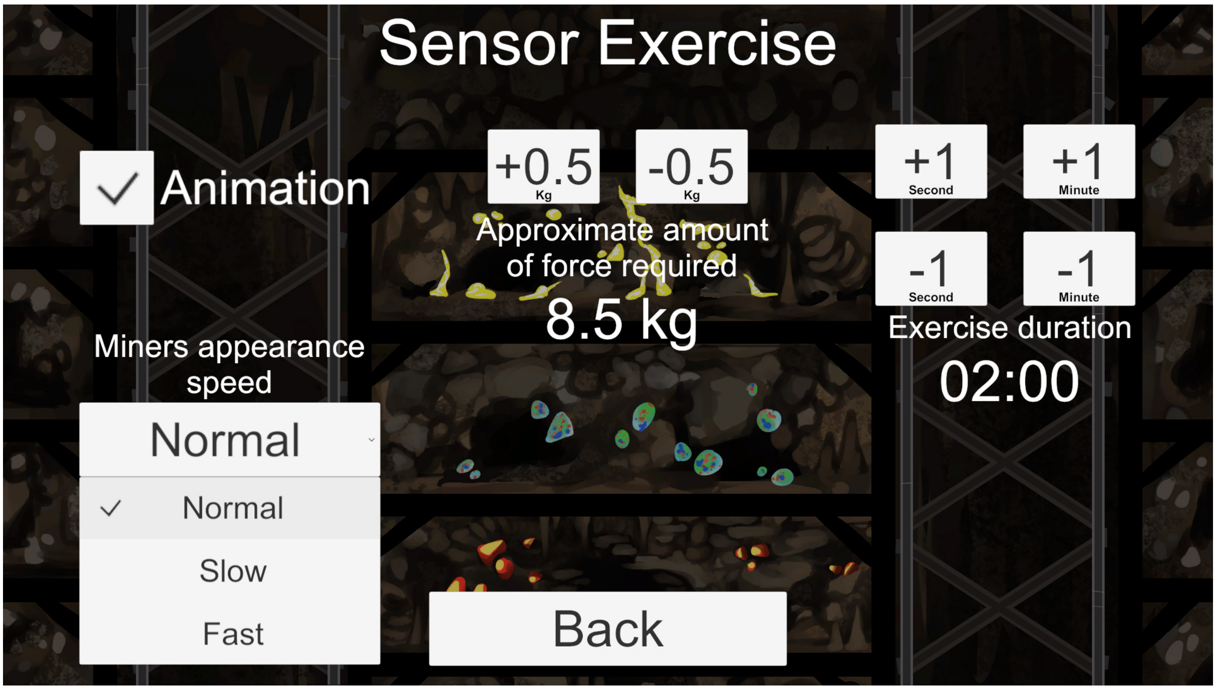


Figure 44: Game settings menu

Figure 45: Start of the game

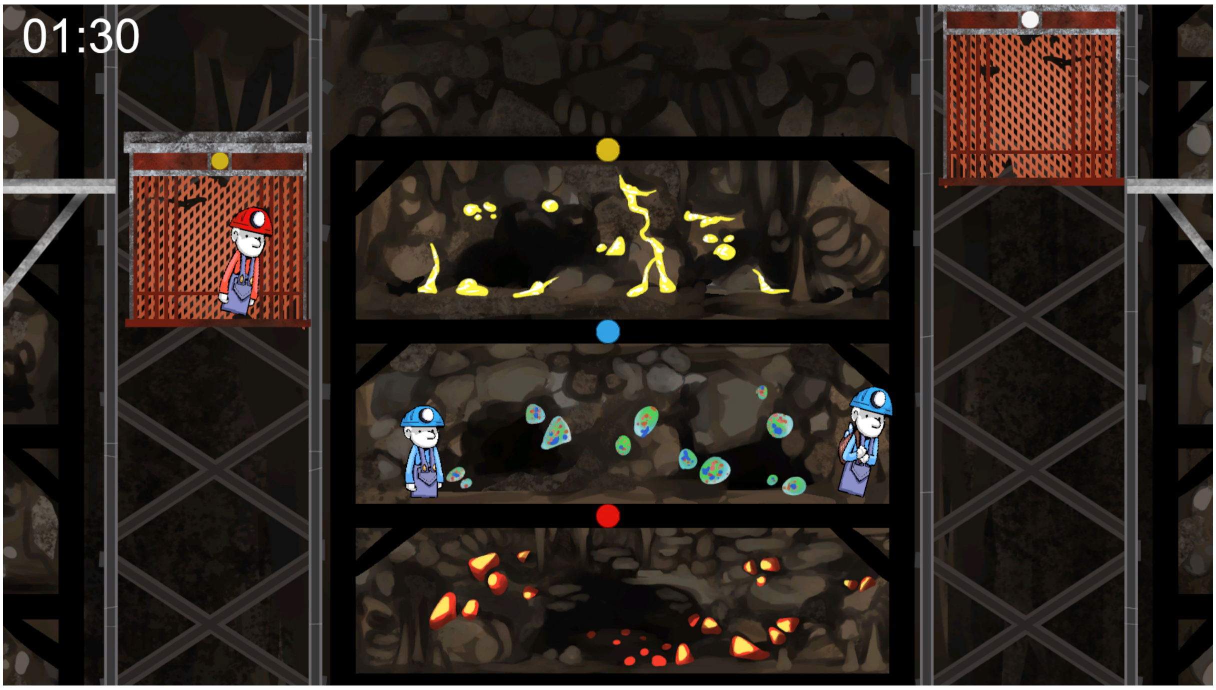


Figure 46: Left elevator working

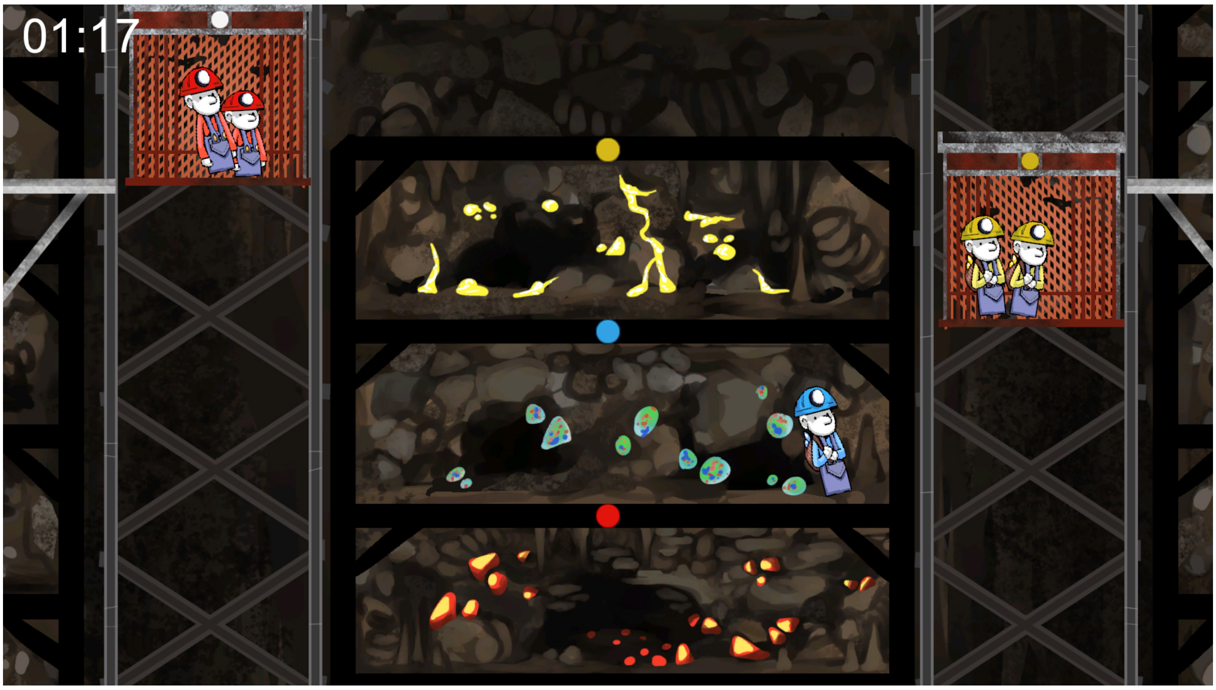


Figure 47: Right elevator working

Appendix 10: Concept drawings

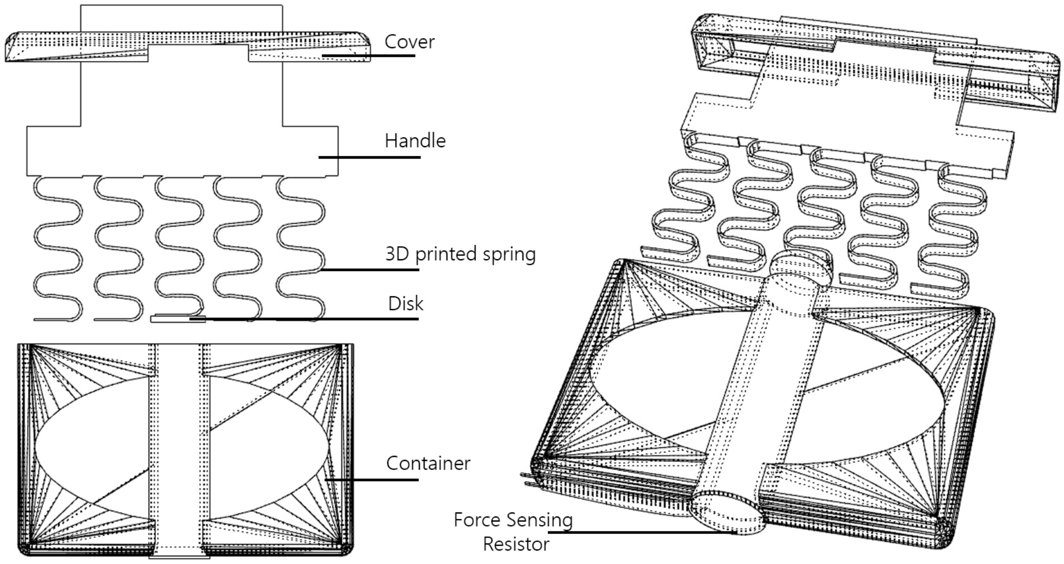


Figure 48: Concept grip trainer version 1.1

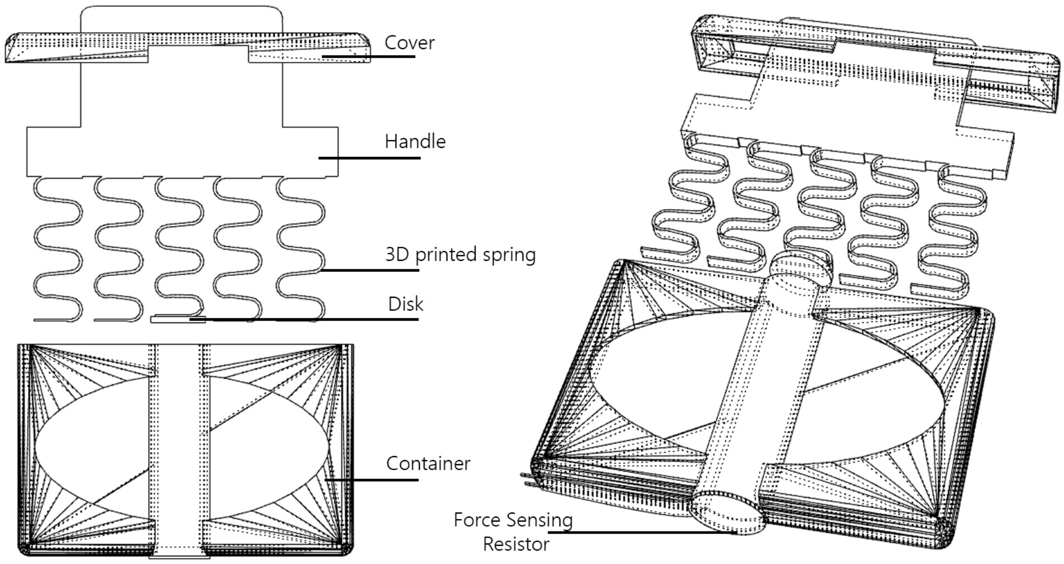


Figure 49: Concept grip trainer version 1.2

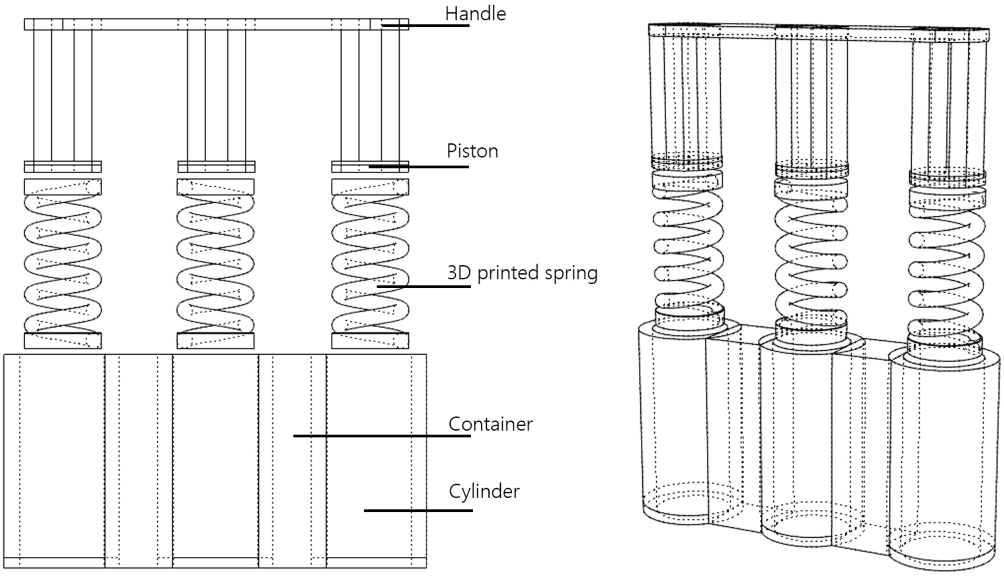


Figure 50: Concept grip trainer version 2.1

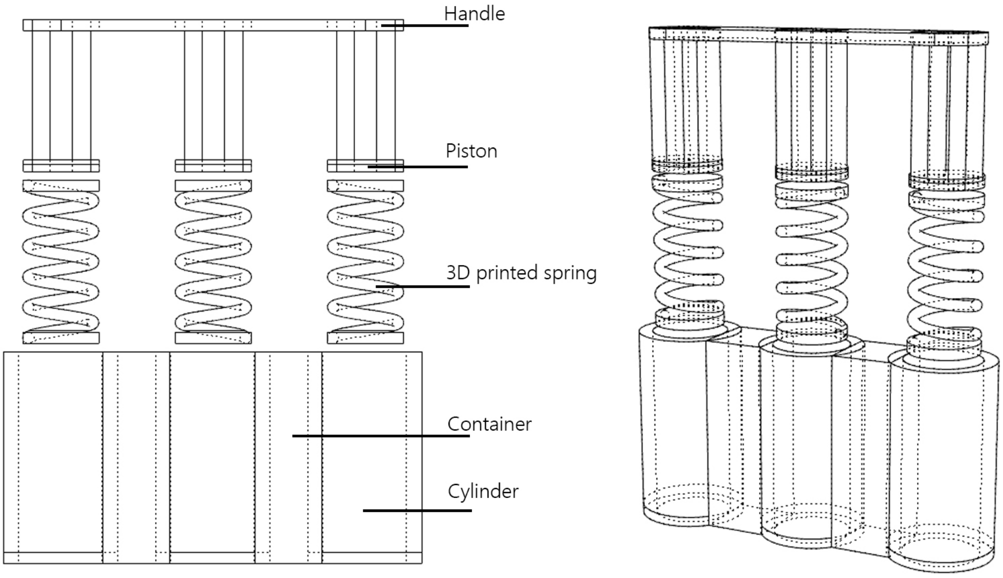


Figure 51: Concept grip trainer version 2.2

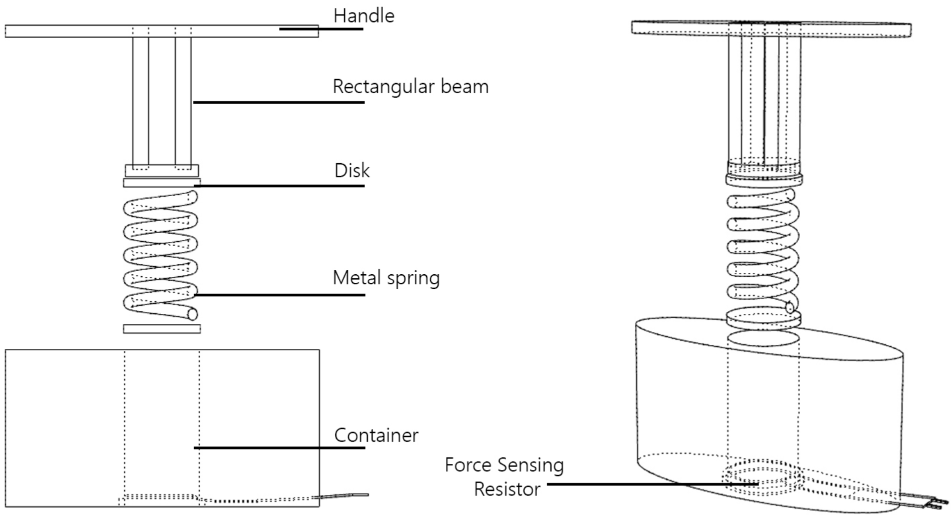


Figure 52: Concept grip trainer version 3.11

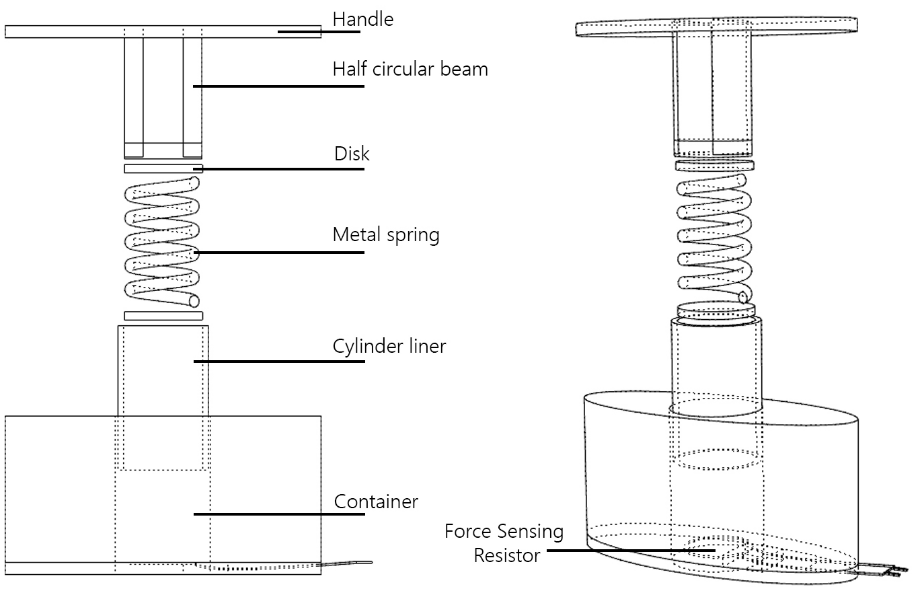


Figure 53: Concept grip trainer version 3.21

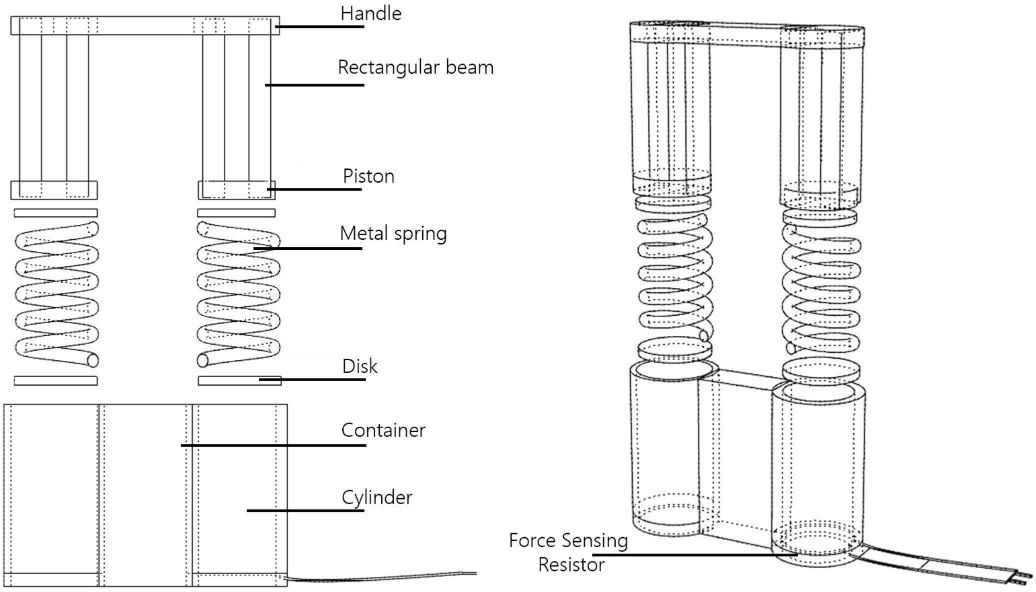


Figure 54: Concept grip trainer version 3.12

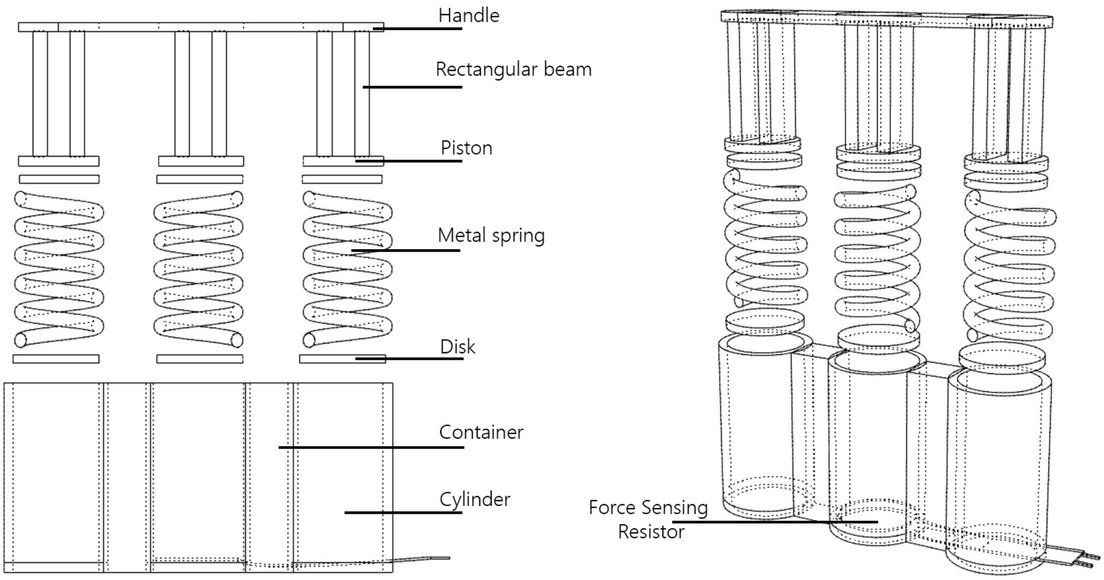


Figure 55: Concept grip trainer version 3.13

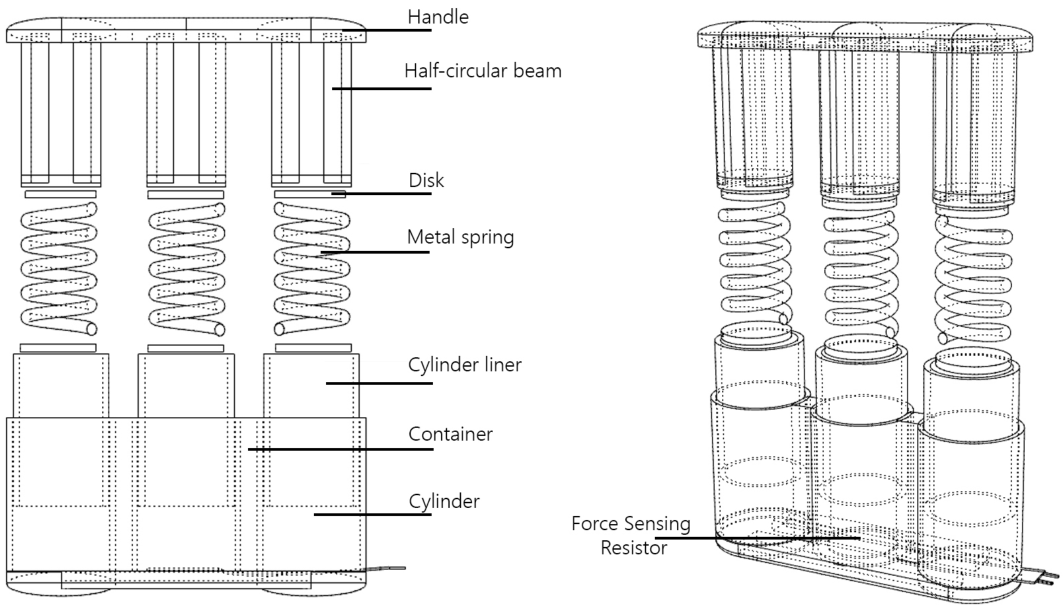


Figure 56: Concept grip trainer final version

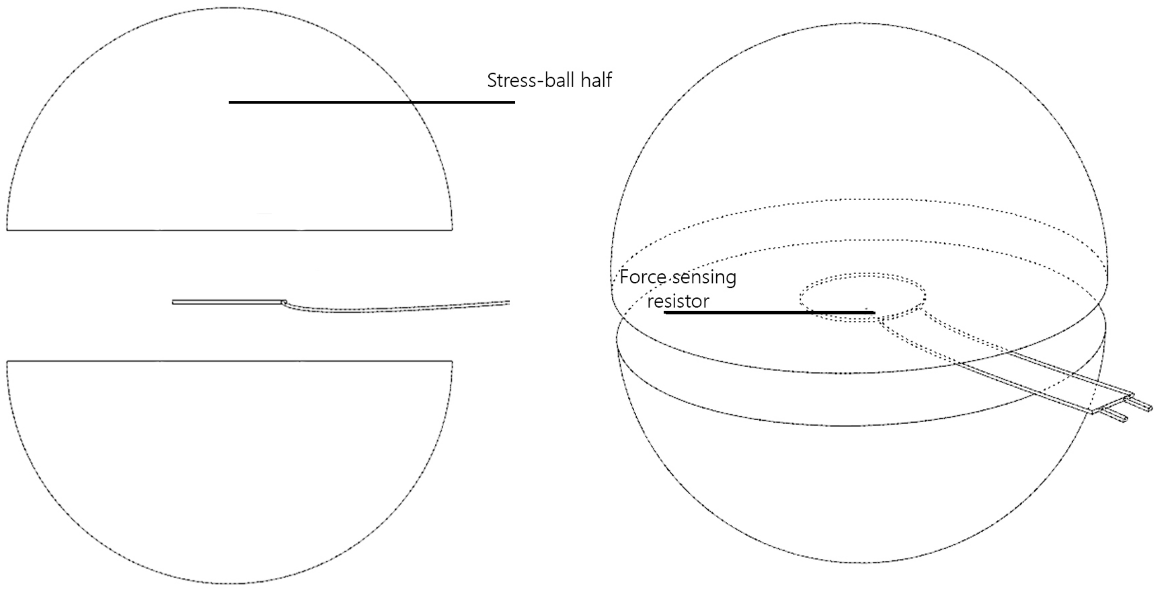


Figure 57: Concept stress ball version 1.1

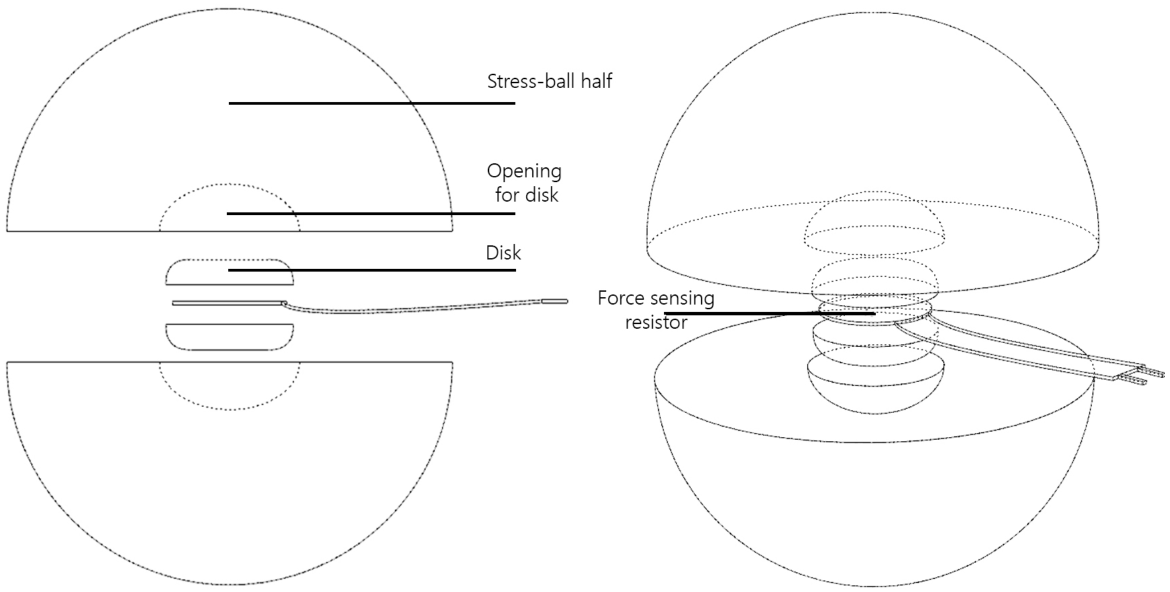


Figure 58: Concept stress ball version 1.2

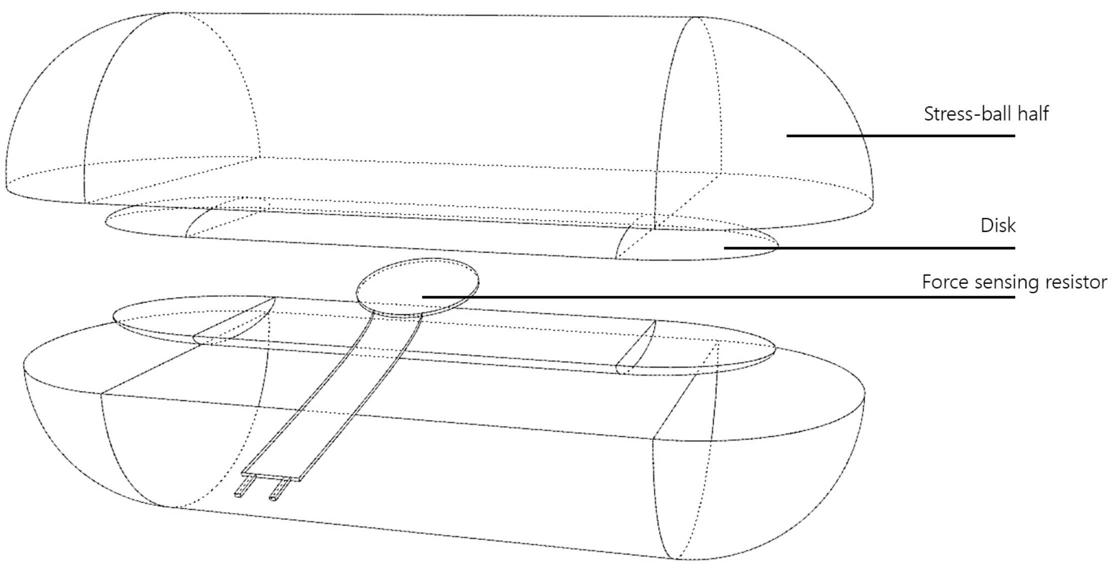


Figure 59: Concept stress ball version 1.3

Table 1 ICU Acquired Weakness

Author	Design/methods	Patients	Measurements	Main findings
Ali NA, 2008	Prospective multi-center cohort study	136	Handgrip dynamometry measured, MRC score	Correlation handgrip strength and hospital-free days. ICUAW is independently associated with increased hospital mortality.
Nordon-Craft A, 2011	Case series study	19	Functional Independence Measure components	Most participants limited to functional activities with baseline median FIM 2.
Chlan LL, 2015	Prospective, descriptive correlational study	120	JAMAR hydraulic hand dynamometer. Serial measurements over time	Diminish in baseline grip strength. From 1 to 102 pounds of force. Older patients had more grip strength diminished.
D. M.-C. De Jonghe B, 2007	Multi-center observational study	116	Maximal inspiratory/-expiratory pressures. Muscle strength measurements in four limbs.	Severed respiratory muscle weakness associated with limb weakness. Significant correlation between MRC score and vital capacity.
Lee JJ, 2012	Prospective observational study	95	Grip strength and disease severity	Muscle weakness reliably predicts mortality. Handgrip strength not independently associated with mortality.
Baldwin MR, 2014	Prospective case controlled study	32	hand-held device for hand grip strength, elbow flexion and knee extension forces	Subjects weaker than control group in respiratory and limb muscle strength measures. Only 20% of subjects capable of returning to pre-admission residence after discharge.
Stevens R, 2009	Prospective multicenter cohort study	116	Maximal inspiratory and expiratory pressure and vital capacity	Respiratory and limb muscle strength are both altered after 1 week of mechanical ventilation.
Brock C, 2018	Prospective multicenter study during 4 weeks	202	Frequency and intensity of mobilisation	Due to barriers like drowsiness an upper limit of feasible mobilisation therapy on the ICU was found.

Table 4: ICU acquired weakness

Table 2 Early mobilisation safety

Author	Design/methods	Mobilisations	Events	Consequences	Results
Hodgson L, 2014	Prospective observation	687	24	some treatments stopped because of different reasons	MRC-SS scores higher in mobilised patients than in control group.
Meyer MJ, 2013	Prospective observation	313	10	1 case of hypotension requiring vasopressors.	mobility score improvement was independently associated with lower hospital mortality
Stiller K, 2009	Prospective observation	69	3	Increased oxygen demand	Increase in exercise time, decrease in needed assistance
Needham DM, 2017	Prospective observation	344	4	Increased oxygen, lying down. No extra care needed.	No significant results.
Bailey P, 2007	Prospective observation	1449	14	Increased oxygen, lying down. No extra care needed	No control group for comparison
Leditschke IA, 2012	Prospective observation	176	2	Return to bed, increase of vasopressors	Mobilisation improved
Morris PE, 2016	NRCT	960	0	No consequences	Protocol patients were on average out of bed 7 days earlier than test group
Brummel NE, 2012	Prospective observation	543	21	One patient with pain, no extra care needed	None
Dafoe S, 2015	Point prevalence study	758	16	Return to bed, drop in blood pressure, replacement of venous line	Improvement in patient mobilisation
Sricharoenchai T, 2015	Prospective cohort study	5267	34	arrhytmias, displaced tubes, 1 fall reported	significant improvement in physical outcomes
Berney S, 2012	Point prevalence study	384	24	Return to bed, Increase expiratory pressure	Patients mobilised more often and longer than in standard care.
Lee H, 2015	Prospective observation	520	26	No events needed extra care	None
Fields C, 2015	Retrospective observation	183	0	No consequences	Study only focused on safety events
McGarrigle L, 2016	Retrospective observation	330	8	Changed position, fluid administration	overall patient performance increased.

Table 5: Early mobilisation safety

Table 3 ICU gaming				
Author	Design/methods	Number of patients	Measurements	Main findings
Kho ME, 2016	Single-center observational study	42	Observed safety and number of incidents	Novel use of interactive video games as a part of routine physical therapy in critically ill patients is feasable and appears to be safe. Video game therapy may complement existing rehabilitation techniques for ICU patients.
Hendriks MMC, 2019	Single-center oberservational study	16	Time/performance in game, peak resistance, general enjoyment.	Patients using interactive in-bed cycling seemed to score better throughout the range. A higher distance was covered, higher peak resistance measured and they seemed to enjoy the video game therapy more.
Laver K, 2012	Single-center observational study. Elderly	44	Functional mobility tests	Significant progression in 2 out of 5 tests. Other tests' progression held no significance.
Kuys SS, 2011	Randomised controlled trial younger adults	19	Cardiovascular condition	No significance was found. Participants did however found the therapy more enjoyable than regular therapy
Sparrer I, 2013	Randomised controlled trial	74	Days in hospital, sensory tests, questionnaire	Non-playing control group stayed 2.4 days longer in hospital (SD=0.5, p¡0.05)
Brem MH, 2010	Controlled clinical trial	32	Memory capacity and intelligence measured by brain-training game	Significant increase in information processing rate and memory span.
Parke S, 2010	Prospective observational feasability study	20	Patient satisfaction, adverse events, technical problems	No severe safety events, patients had problems with fatigue and discomfort, 25% of the games had technical issues, nearly all patients found the games enjoyable and wanted to play again.

Table 6: ICU gaming

Table 4 Wii-gaming for post-stroke rehabilitation				
Author	Device	Study design	Number of patients	Main findings
Imşek TT, 2015	Nintendo Wii	RCT	42	Significant improvement in quality of life and ADL
Yatar GI, 2015	Nintendo Wii	RCT	30	Significant improvement in balance, balance confidence and ADL
Hung JW, 2015	Nintendo Wii	RCT	30	Significant improvement in motor function and fear of falling.
Morone G, 2014	Nintendo Wii	RCT	50	Significant improvement in balance.
Bower KJ, 2014	Nintendo Wii	RCT	30	Trends towards improved balance and arm function (though no significance was found)
Lee, 2013	Nintendo Wii	RCT	24	Significant improvement in functional reach and static balance.
Barcala L, 2013	Nintendo Wii	RCT	20	Significant improvement in balance, body function and symmetry.
Saposnik G, 2010	Nintendo Wii	RCT	22	Significant improvement in mean motor function and grip strength. No adverse events.
Choi JH, 2014	Nintendo Wii	RCT	20	Significant improvement in manual functions, box and block test, daily activities, cognitive function and grip strength.
Yong Joo L, 2010	Nintendo Wii	Observational study	20	Significant (though small) improvements in FMA and motoricity scores.
Mouawad MR, 2011	Nintendo Wii	Observational study	12	Significant improvement in functional movement in all patients.
Hijmans JM, 2011	CyWee Z (comparable to nintendo wii)	Cross-over study	14	Significant improvement of motor performance and motivation. No changes in secondary outcomes.

Table 7: Nintendo Wii gaming

Table 5 Playstation and Xbox gaming for post-stroke rehabilitation

Author	Device	Study design	Number of patients	Main findings
Yavuzer G, 2008	Sony Playstation	RCT	20	Significant improvement in functional independent measurements.
Neil A, 2009	Sony Playstation	Observational study	20	Active gaming provided more upper extremity repetitions than conventional therapy.
Rand D, 2008	Sony Playsation	Observational study	12	All patients enjoyed the games, but only 1 patients appeared to have physical benefits.
Sin H, 2013	Xbox kinect	RCT	40	Significant improvement in upper limb function.
Song GB, 2015	Xbox kinect	RCT	40	Significant improvement in balance, gait and depression.
Lee, 2013	Xbox kinect	RCT	14	Significant improvement in upper extremity muscle strength and ADL.

Table 8: Playstation and Xbox gaming

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