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Development of Rehabilitation Apparatus for Whiplash Patients

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Preface

The master's thesis is a scientific project conducted through the last semester of a five years masters degree at the Norwegian University of Science and Technology (NTNU). The thesis is a final assessment and is mandatory in order to obtain the Master of Science degree.

This is the 5th master thesis that has been conducted on the matter, and it has been written for the Department of Mechanical and Industrial Engineering at NTNU. The project started in 2014 by request from Firda Physical Medicine Center to develop a new and improved apparatus for whiplash rehabilitation. The project involves experimental work which has been evaluated through the risk assessment found in Appendix I.

The current project started at the 14th of January 2018 with a deadline of 11th of June 2018.

Stian Krogstad Brattgjerd has a Bachelor's degree in mechanical engineering and is currently carrying out a Master's degree in mechanical engineering at the Department of Mechanical and Industrial Engineering. Andrea Marie Festøy is carrying out a Master's degree in Engineering and ICT with specialization in mechanical engineering. This program contains a combination of courses in mechanical and computer engineering.

Problem description

This assignment should focus on further development of an apparatus used for recovery training of whiplash patients. The development should advance as far as possible, and will preferably resolve into a proof of concept prototype. There are mainly four major components of the apparatus to be developed:

- *Investigate the robotic arm Panda, as the motion platform*
- *Head mount*
- *Seat for the patient*
- *Framing the structure of the apparatus*

Summary

Firda Physical Medicine Center (FPMC) specializes in diagnosis and rehabilitation of neck injuries. Today FPMC conducts part of their rehabilitation training through an apparatus called the Multi-Cervical Unit (MCU). The MCU is an apparatus that restricts the patient to rotate his/her head in only one plane, while producing resistance against the movement, thus training their neck muscles. However, FPMC is not pleased with the MCU. The MCU is old fashioned, and as an example only allows rotation in three directions. A partnership between FPMC and NTNU was established with the intent of developing a new training apparatus. Numerous designs and prototypes have been developed in previous projects. The latest project recommended investigating a design where a robotic arm is used to provide resistance. The project recommended the use of the robotic arm Panda from Franka Emika due to its attractive price and advanced sensor technology.

The scope of this master's thesis was to continue the development by a feasibility study of using the robotic arm Panda to provide resistance. The robot's workspace and load capacity were to be tested and incorporated into an apparatus. The robot arm would need to be placed on a rigid surface (frame structure) which would provide a suitable position relative to the patient's head. In addition, a suitable tool allowing the patient's head to be fixed to the robot (head mount) was needed. The head mount would have to fit different head sizes and create comfort for the user. This master thesis aimed to accomplish both simulations of the robotic arm Panda and to build a proof of concept prototype of the frame structure and head mount.

The load capacity and workspace of Panda were simulated using a computer model. The simulations showed that Panda failed to deliver the specified training space as it could not deliver full backward bending with the current base position of the robot. When executing backward bending the robotic arm is retracted to the extent that it collides with itself. The simulations showed that the load capacity of Panda is adequate. The proof of concept prototype was realized, including the frame structure and head mount. The head mount was constructed from an alpine helmet and inflatable inserts. It seems to be a good solution since it fits different head types and acts as a strong enough fixing point to handle the forces related to the resistance.

Recommendations for next stage in the development are to evaluate if Panda can deliver the training space with modifications of the base position. Feedback from patients on the proof of concept prototype should be collected to decide on further design and development. A compromise between training space, cost and size may be unavoidable.

Sammendrag

Firda fysikalsk-medisinsk senter (FFMS) spesialiserer seg i diagnostisering og rehabilitering av nakkeskader. I dag blir deler av rehabiliteringsprosessen gjort gjennom et treningsapparat ved navn Multi-Cervival Unit (MCU). Treningsapparatet bruker vekstskiver som motstand for å trene opp områder hvor nakkens funksjoner er nedsatt på grunn av skade. Apparatet ble utviklet på slutten av 90-tallet, og har ikke blitt videreutviklet siden. FFMS er ikke fornøyd med MCU på grunn av restriksjoner i bevegelsesbaner og dårlig dataregistrering under øvelsene. Dette resulterte i et samarbeid mellom FFMS og Norges teknisk-naturvitenskapelige universitet (NTNU), for å utvikle et nytt og bedre treningsapparat. Mange konsepter har hittil blitt utviklet, og vurdert. Det siste prosjektet konkluderte med å undersøke om robotarmen Panda fra Franka Emika kan brukes til å yte motstand.

Omfanget for denne masteroppgaven var å fortsette arbeidet med en mulighetsstudie basert på Panda. Prosjektets mål var å teste robotens arbeidsområde, evne til å yte tilstrekkelig motstand og designe en løsning for å innkorporere armen i et apparat. Apparatet må ha en stabil innfestning for roboten, og i tillegg gi en optimal plassering med tanke på robotens arbeidsområde for å dekke de nødvendige opptreningsbanene. Videre trenger apparatet en hodeinnfestning for å feste roboten til pasienten. Denne hodeinnfestningen må kunne tilpasses forskjellige hodeformer, samt være komfortabel. Planen for denne oppgaven var å bygge fungerende prototyper av rammekonstruksjon og hodeinnfestning, samt kartlegge potensialet for å bruke Panda til opptrening.

Gjennom en datamodell i Matlab ble Panda testet med hensyn på treningsområde og motstand. Alle lastsimuleringer viste at roboten håndterte lasten som krevdes. Det samme gjaldt treningsområde med unntak av bakoverbøy. Det viste seg at under bakoverbøyning må leddene i Panda rotere så mye at roboten krasjer i seg selv. Funksjonelle prototyper ble realisert av hodeinnfestningen og rammekonstruksjon. Hodeinnfestingen består av en alpinhjelm med oppblåsbare elementer på innsiden. Tester ga gode indikasjoner på at en slik hodeinnfestning vil fungere bra med kreftene levert fra robotarmen.

For at Panda skal ha mulighet til å levere det optimale treningsområdet, må tester utføres for å finne en annen plassering av roboten. Hvis det viser seg at roboten uansett ikke klarer å levere treningområdet, er en mulighet å redusere området, eller finne en større robot. Det siste kan bli problematisk med tanke på resurser, og det må muligens foretas et kompromiss mellom størrelse, kostnad og treningsområde. Sett bort fra robotarmen, har de fungerende prototypene nesten full funksjonalitet i alle andre krav. Det er derfor anbefalt at rammekonstruksjonen og hodeinnfestingen blir testet av pasienter for å samle tilbakemeldinger for senere utvikling.

We would like to especially thank our supervisors Knut Einar Aasland and Kristoffer Bjørnerud Slåttsveen, for assisting us during the period of the master thesis. We would also like to thank Morten Leirgul at Firda Physical Medicine Center for always being available for questions and other inquiries. The employees at the MTP realization lab for assisting us with practical help at the workshop. Levanger municipality for providing us with an office chair for our prototype. Sigmund Festøy for proof reading and valuable feedback, and the rest of our family and friends for great support and help. Finally, we would like to thank each other for the great cooperation and learning value during the project.

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Abbreviations

ABS = Acrylonitrile Butadiene Styrene
BLDC = Brushless Direct-Current
CAD = Computer Aided Design
CAE = Computer Aided Engineering
CNC = Computer Numerical Control
DFA = Design For Assembly
DFM = Design For Manufacturing
DH = Denavit–Hartenberg
DoF = Degrees of Freedom
DPDT = Double Pole, Double Throw
DTM = Design Theory and Methodology
FPMC = Firda Physical Medicine Center
GTT = Glass Transition Temperature
MCU = Multi-Cervical Unit
MTP = Department of Mechanical and Industrial Engineering
NPD = New Product Development
PD = Product Development
PLA = Polylactic Acid
PVC = Polyvinyl Chloride
RHS = Rectangular Hollow Section
TCP = Tool Center Point
WAD = Whiplash-Associated Disorders

Nomenclature

a = DH-parameter for the translation along the x_{n-1}-axis
α = DH-parameter for rotation around the x_n-axis.
d = DH-parameter for the translation along the z_{n-1}-axis.
θ = DH-parameter for the angle of rotation around the z_{n-1}-axis.
ϕ = Angle of force vector during forward bending.
$\vec{q}$ = Vector of the robots joint angles
$\vec{p}$ = Pose of reference frame in end effector
$\vec{F}$ = Force vector

Chapter 1

Introduction

1.1 Background

It is estimated that around 26 000 Norwegians suffer from neck related injuries every year. The most common form of injury is whiplash due to high momentum accidents. The type of accidents varies, but the most frequent ones are car crashes or sports injuries. The extent of damage varies from mild and moderate cases, where simple over the counter drugs and self-healing will suffice, to more severe cases where regularly recovery training and follow-ups are needed. In the few worst-case scenarios, medical surgery must be performed. The Norwegian association of neck trauma has estimated that as much as 400 people in Norway become entirely occupationally disabled each year due to whiplash. Also, as many as 1 350 people get partially disabled. The most common symptoms of the neck trauma are headaches, reduced neck movement, along with pain, dizziness and nausea [1, 2, 3].

Sandane, in Norway, has one of the few facilities that specializes on whiplash treatment in all of Scandinavia, and in 2014 a partnership between Firda Physical Medicine Center and NTNU, Department of Mechanical and Industrial Engineering (MTP) was established. FPMC believe that one of the solutions to treating moderate to severe whiplash cases is by doing recovery training of the muscles around the damaged area. In this regard, FPMC has used a training apparatus called the MCU, or the Multi-Cervical Unit. The apparatus can isolate the appropriate muscles in the neck to focus the recovery training on the damaged area. The MCU, along with the professional help and guidance of the employees at FPMC, has an excellent track-record, and as many as 215 out of 222 people have given feedback that their treatment at FPMC has improved their situation [4].

However, there is room for improvement with regards to the MCU. The apparatus is old-fashioned, poorly adjustable and does not permit an appropriate user interface for an optimized treatment. It has been conducted four specialization projects and master's thesis on the development of a new apparatus. Three different concepts have been evaluated, but unfortunately, they all met different challenges and were subsequently discarded. The most recent thesis written by Thomas Erik Lyngman Gælok and Michelle Strand concluded that a robot arm could be a viable solution as the motion platform. This seemed like a promising solution, and it was concluded to continue the project and research the use of a robotic arm.

Stian Krogstad Brattgjerd started the work on this concept with a specialization project in the autumn of 2017. The robotic arm is the crucial component of the apparatus, and the project needed more competence in cybernetics and computer engineering. Therefore, Andrea Marie Festøy was included in Brattgjerds master's thesis. A specialization project by Shahrukh Khan at Department of Engineering Cybernetics was also established to investigate the control theory of the robotic arm.

1.2 Problem

The MCU is an old-fashioned device with unfortunate limitations. Today the MCU only offers sensor feedback on the angular displacement. FPMC would ideally have more feedback during the training, preferably force, speed, etc. This would allow the physiotherapist to map the training, compare sessions, and observe the progression, thus improving the rehabilitation.

However, the most significant disadvantage of the MCU is the motion restriction, only allowing rotation around the three axes inside the fixture of the apparatus. This allows the patient to train in only three different paths: backwards/forwards-, sideways- and rotational motion. Each patient has a unique case of whiplash, and requires a customized training program. The option to train in motion paths that include combinations of the three main motions would be a considerable improvement and allow each training program to be even more custom made. A motion platform that allows rotation around the neck of the patient instead of around the fixture of the apparatus would also increase the efficiency of the session.

Whiplash patients often lack muscles and ligaments to stabilize the head when performing the motion path. Because of this, patients will tend to move the head out of the desired motion path. It is essential that the motion platform could create virtual walls restricting the patient to follow the correct path.

Today FPMC is the only center in Norway offering this level of whiplash treatment [5], which is unfortunate regarding the extent of people with whiplash injuries. A solution would be a motion platform that can be operated by any physiotherapist, after the training program is formed. This would result in patients being able to do the rest of the recovery training at a local physiotherapist center.

1.3 Agenda

Based on the past research and the issues with the MCU, the robotic arm is a viable solution. To incorporate the robotic arm into an apparatus for rehabilitation purposes, additional components and elements must be developed. The challenges for using a robotic arm as a motion platform are as follows:

- A suitable end effector to interact with the patient's neck (head mount)
- A stable and comfortable seat for the patient
- A durable frame structure for integrating the motion platform with the seat

The ambition of the thesis is to develop and realize a proof of concept head mount, seat and frame structure to go with a robotic arm. The robotic arm is not acquired or funded. Therefore, it will not be included in the finished prototype, but a feasibility study of the motion platform will be conducted to conclude on the robotic arms potential.

Chapter 2

Theory

This chapter is included to cover the theory needed for understanding the thesis. Firstly it covers the medical theory related to the neck and whiplash. This consists of anatomy of the neck, whiplash, treatment, and medical devices in medicine. Secondly, the chapter includes a section on robotics, which ensures that the readers have the needed background to follow concepts and methods used later in the thesis.

2.1 Anatomy of the human neck

Due to its different shapes and structures enclosed around a relatively small area, the human neck is considered to be one of the most complex parts of the human body. The neck is also treated as one of the most vulnerable, as it contains several vital organs including big blood vessels, nerves, and the spinal cord [6]. The purpose of the structure is to connect the head with the torso along with providing adequate mobility.

The neck is located at the uppermost part of the spine and accounts for seven of a total number of 33 vertebrae along the length of the spine. The necks structure gives the head a range of approximately 6-degrees of freedom [7], and the pattern of movement is usually rotation, flexion, and extension. The necks vertebrae are called (counting from top to bottom), C1, C2, C3 and so on (Figure 2.1) all the way down to C7.

The two uppermost vertebral C1 and C2, or more commonly known as Atlas and Axis, stands out from the remaining five. The reason being that they provide a much greater deal of mobility. C1 acts as a ring/washer that the skull rests upon, thus providing most of the rotational movement of the head. Due to the configuration of C2, it is responsible for most of the flexion and extension of the head [8].

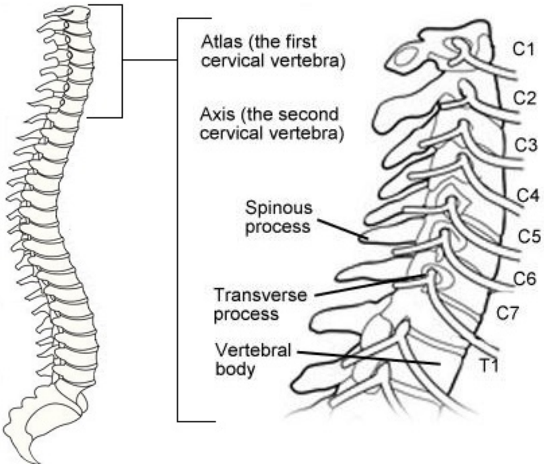


Figure 2.1: Cervical spine anatomy [8, 9].

Each cervical vertebral is attached to one or several muscles, that can cause movement of the neck when they contract or relax. Since these muscles keep the head in an upright position all day, they are incredibly enduring, and damage to these muscles could be critical.

2.2 Whiplash

Whiplash is a phenomenon that involves a sudden acceleration or deceleration of the body. The acceleration is often unanticipated, and the human brain is unable to react fast enough. This causes the head to bounce back and forth in a very displeasing manner, and will in worst cases have a catastrophic outcome for the victim [10]. The most common events causing whiplash is traffic collisions and sports accidents, but lighter versions can occur in daily life activities.

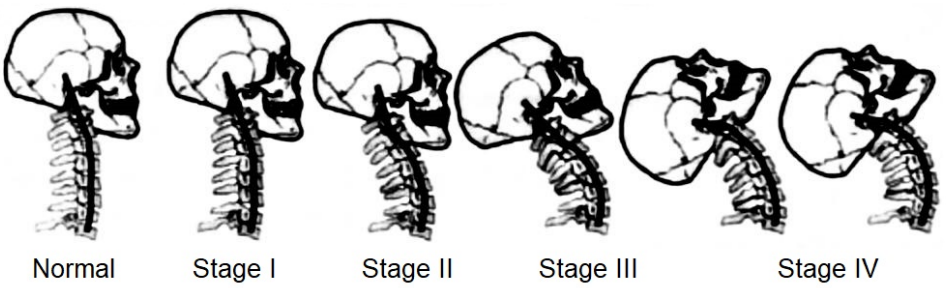


Figure 2.2: Whiplash mechanism [11].

In 2009, Mr. Chen Hai-bin, King H Yang, and Wang Zheng-guo released a paper investigating the kinematics of whiplash accidents, by doing experiments on cadavers and volunteers. Their study shows that the mechanics are narrowed down to four stages. In the first stage, a flexural deformation of the neck is observed along with a loss of cervical lordosis, which is a term for the normal curved shape of the cervical (Figure 2.2). In stage two the cervical spine creates an S-shaped curve, as the lower vertebrae begin to extend and gradually cause the upper vertebrae to extend. At the third stage, the entire neck starts to extend, and in the fourth and final stage, the neck is fully extended due to the extension moments in both the upper and lower cervical vertebral [12].

However, there is evidence that the mechanism of a whiplash injury varies with the extent of the forces at work. The damage is also a very disputed matter due to the complexity of the cervical. The forward and backward jerking motion could cause damage to ligaments causing them to deform plastically (Figure 2.3, g), which means they will not return to their normal position and shape. In more severe cases, damage to joints (b, c, e), vertebrae (a, d, f, j), muscles and/or nerves can occur. An absolute worst case, can result in completely torn ligaments (h, i) [13, 14].

Hai-bin and his associate's argue that injuries to the facet capsule region (b) of the neck are the major sources of post-injury pain, and discloses several hypotheses related to strains within the facet capsule due to events in the early stages of impact (stage I and II) [12].

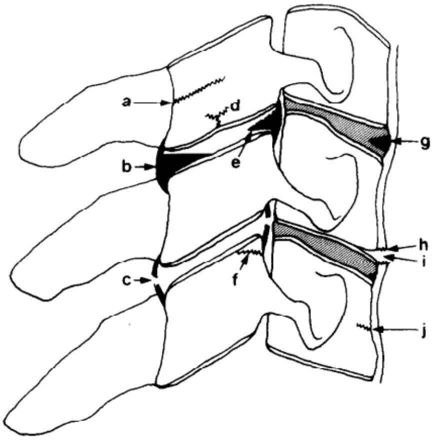


Figure 2.3: Common lesions concerning whiplash: Damage to vertebrae(a, d, f, j), damage to joints(b, c, e), plastically deformed ligaments(g) and torn ligaments(h, i) [14].

2.2.1 Treatment

Problems linked with victims of whiplash or people with Whiplash-associated disorders (WAD) mainly depends on which type of injury they have sustained [15]. As stated, the main types of damage are related to muscle-, nerve-, bone- and joint damage [5]. How these forms of injuries are treated, dependents on the extent of the damage. Light to moderate injuries can be treated by self-care advice and over the counter drugs in order to relieve the pain [16]. In more severe instances, the need for more disciplined recovery training by physiotherapists are needed (Figure 2.4). In the worst or extreme cases, the need for medical surgery is inevitable.

Figure 2.4: Manual therapy of whiplash patient [5].

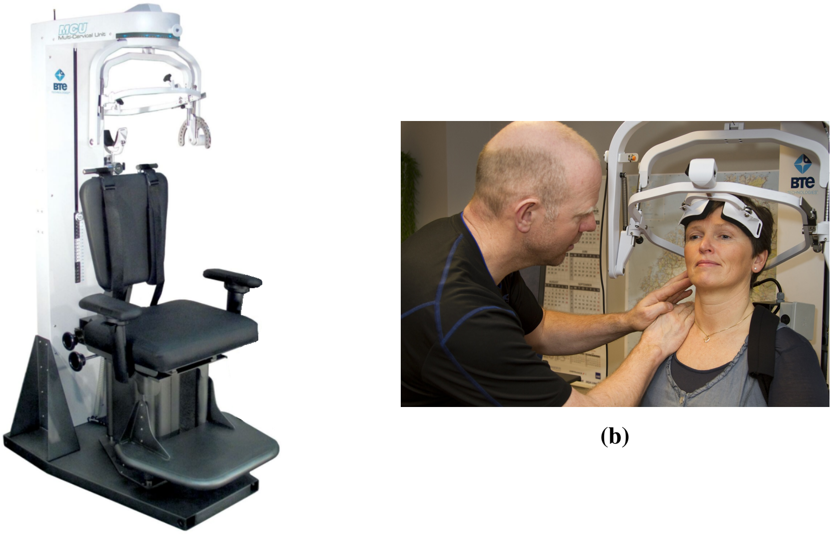
The physiotherapists at Firda Physical Medicine Center in Sandane, have the understanding that when the ligament and muscles in the neck get afflicted by whiplash, they weaken. As a result, the neck's ability to carry the weight of the head is reduced. The body's reaction is to initiate the muscles around the damaged area to atone for the extra load. Over time, these muscles become overworked and result in pain [5].

To treat this problem, the experts at FPMC use their diagnostic experience to localize the damaged region of the neck. The next step is to create an exercise program to strengthen the surrounding muscles, and in this way compensate for the damaged body parts. The exercise program involves individual follow-up by the physiotherapists at FPMC through manual/physiotherapy, self-rehabilitation and training in the training apparatus called the MCU, or the Multi-Cervical Unit.

2.2.2 Multi-Cervical Unit

The MCU is a training apparatus (Figure 2.5a) developed by a company called BTE tech. It is an American company and specializes in human physical performance evaluation and treatment. The apparatus was developed in the 90s. The MCU works in the way that it provides a weight-based resistance against the patient's movement of the head. The resistance can be adjusted depending on the severity of the injury. When the patient's condition improves, more weights are added [17].

The patients head is fixed inside the head mount using four surrounding pads. Each pad is screwed against the back- and forehead of the patient. To keep the rest of the patient's body still, a four-point seat belt is used. When the patient is properly fixed, training can commence. At this time, the MCU is used like any other training apparatus. It allows for either forwards/backward, sideways, or rotational motions of the head (Figure 2.5b).



(a) **(b)**

Figure 2.5: Multi-Cervical Unit (a) and treatment in MCU (b) [5, 17].

A questionnaire conducted by FPMC reveals that 215 out of 222 patients experience significant improvement after their treatment involving the MCU [4]. However, the apparatus was developed over 20 years ago, and has not been noteworthy enhanced since. Additionally, BTU tech has no plan to further develop it.

2.3 Medical devices in medicine

Medical equipment is defined in the Norwegian legislation as an instrument, apparatus, appliance, material, software or other articles, necessary for the proper application, intended by the manufacturer to be used for human beings with the purpose of:

- diagnosis, prevention, monitoring, treatment or alleviation of disease,
- diagnosis, monitoring, treatment, alleviation of or compensation for an injury or handicap,
- investigation, replacement or modification of the anatomy or a physiological process,
- control of conception,

and which does not achieve its principal intended action in or on the human body by pharmacological, immunological or metabolic means, but which may be assisted in its function by such means. Additionally, an *active medical device* is defined as medical equipment that needs power or another source of energy to operate, not using kinetic energy from the patient or gravity [18].

2.4 Robotics

For this project, a robotic arm is used as part of the apparatus. This section is included to give a short introduction to the most important topics of robotics, used in this master's thesis.

Robotic Arm

Definition from [19]. *A robotic arm is a type of mechanical arm, usually programmable, with similar functions to a human arm; the arm may be the entire mechanism or may be part of a more complex robot. The links of such a manipulator are connected by joints allowing either rotational motion (such as in an articulated robot) or translational (linear) displacement. The links of the manipulator can be considered to form a kinematic chain.*

Degrees of freedom

A robotic arm is usually defined by its degrees of freedom. The robots number of joints defines the degree of freedom. Each joint adds one degree of freedom to the robot. For the robot to be able to move in all positions and rotations in a 3D space, at least six degrees of freedom are required. Three degrees of freedom for the position, and three for the orientation.

Pose

A pose is the collective term of the position and orientation of an object.

Kinematic Chain

A kinematic chain is a series of rigid bodies (links) that are connected by joints. Kinematics is only the geometric entities of rotation and translation and does not refer to mass, friction, torque, etc. this is called a dynamic chain. Kinematics is a potent tool to calculate rotational and translational motions and also linear and angular velocities.

Joints

There exist several types of joints, but the two main categories are prismatic and revolute joints. A prismatic joint is a joint that allows linear translation between two links. A revolute joint is a joint that allows rotation between two links (Figure 2.6). Each joint in a kinematic chain adds one degree of freedom to the manipulator. When using a kinematic chain one reference system is placed in each joint.

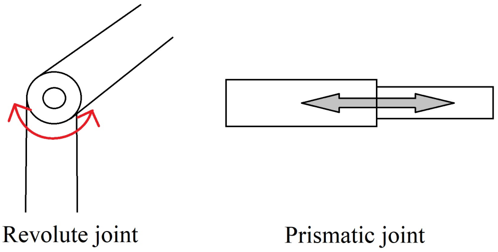


Figure 2.6: Illustration of revolute and prismatic joint.

End effector

A robotic arm normally consists of several links ending in an end effector also called gripper, hand, end tool and more. The end effector has a tool with the right characteristics for the desired task. The end effector has a tool center point (TCP), which is the point where the trajectory and position of the end effector is calculated.

Task space and joint space

The space where the arm of the robot moves is called the joint space, while the space where the end effector operates is called the task space. The joint space is given as a vector of each of the joints and generally described with a $\vec{q}$. The dimensionality of $\vec{q}$ equals the number of joints in the chain (Figure 2.7).

The task space consists of a vector describing the pose of the reference frame in the end effector. The pose in a three-dimensional space will be a six-dimensional vector. The three first values are the position, and the final three are the orientation of the reference frame.

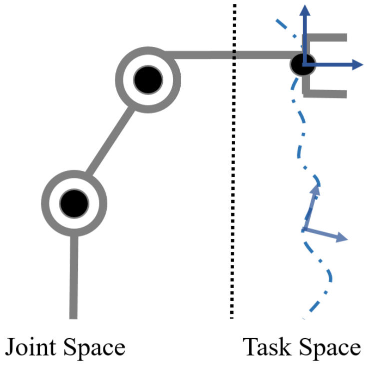


Figure 2.7: Illustration of task space and joint space.

Open and closed chains

Open chains are mostly used for robotic arms, but if the load is too heavy and require a more sturdy structure, closed chains are useful. A closed chain is a configuration that have more than one chain connected to the end effector. Note that this increases the complexity and reduces the task space. It also increases the risk of singularities.

Singularities

It is essential to consider singularities when choosing an appropriate robot. Singularities can happen when two robot axes (or more) align, which causes the robot to behave unpredictably, or not move at all. This is one of the reasons human-like robots have bent knees. This phenomenon happens when a robot arm does not have a sufficient amount of DoFs, or it is moving to a position causing singularities.

Kinematic functions

Kinematic functions are used to calculate the kinematic properties of a robot. Direct kinematics calculates the task space variable based on the joint space variable. This is an easy computation with only one solution. The opposite is the inverse kinematics which calculates the joint space variables based on the task space variable (Figure 2.8). There will often be more than one solution in the joint space to obtain the desired pose in the task space. The complexity of the operation increases with the DoF because the increased number of joints adds unknowns to the equation. Because of this, an approximation of the joint space vector is used as a start point of the calculation.

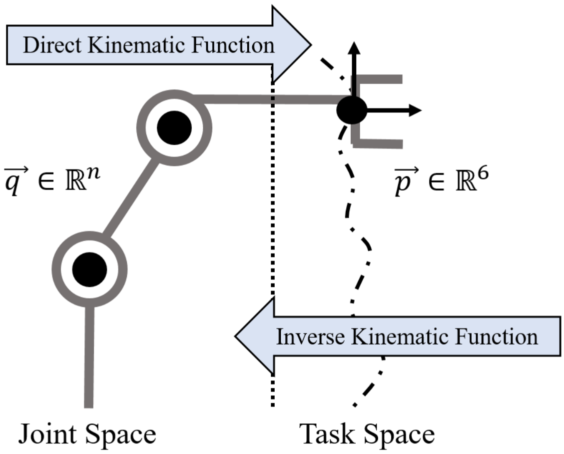


Figure 2.8: Illustration of kinematic functions.

Dynamic function

Dynamic functions are the equivalent to kinematic functions, but includes dynamic parameters such as mass, force, and torque.

Denavit-Hartenberg convention

For computing kinematics, a reference system in each joint is required. The relation between these systems needs to be stated. Normally six parameters are needed to describe both the position and orientation between each reference frame. The Denavit-Hartenberg parameters usually referred to as the DH-parameters, only needs four parameters to describe the relationship between each reference frame.

The four DH-parameters are θ, α, d and a. d and a are related to translation and θ, and α for rotation. d, a and α are only related to the geometry of the robot and are constant in time. θ is related to the motion of the joint and changes relative to time (Figure 2.9).

- θ is the angle of rotation around the z_{n-1}-axis for revolute joints or distance of translation for prismatic joints.
- d is the translation along the z_{n-1}-axis.
- a is the translation along the x_{n-1}-axis
- α is rotation around the x_n-axis.

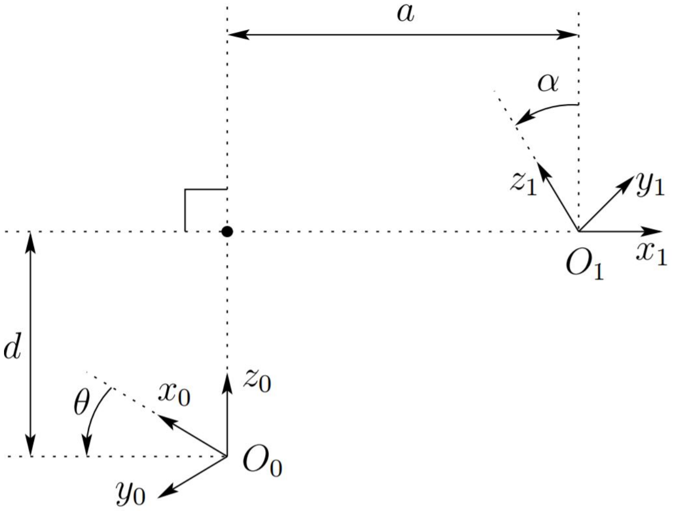


Figure 2.9: Illustration of the DH-parameters [20].

For a more detailed description of the DH-convention, please read chapter three in Robot Dynamics and Control by Mark W. Spong, Seth Hutchinson, and M. Vidyasagar [20].

Chapter 3

Methods

During the development process of the upcoming concepts, different product development methods have been applied. To greater understand the process, the relevant methods will be disclosed in the upcoming sections.

3.1 New product development

New product development (NPD) is defined as the process of transforming a market opportunity along with a set of assumptions about product technology, into a finalized product available for sale [21]. The success of a new product depends on a firms understanding of customer needs and the business environment, as well as the market demand and conditions [22]. In short, NPD is a process that covers everything needed to bring a new product or service into the market. To be successful in NPD, knowledge is key. Recognizing the importance of customer needs and wants, competition, cost, time and how to develop, increases the chances of developing something that would benefit the company. From an engineering perspective, knowledge about the development process is vital, and key elements are explored in the following subsections.

3.1.1 Design theory and methodology

Design theory and methodology (DTM) refers to the theory and methods utilized when developing a concept, idea or product for a specific situation. It focuses towards how we design, rather than what we design. To be successful in activities such as product development and design, knowledge of DTM will have a significant impact on obtaining the most favorable result based on resources and time available. It is all about choosing the correct development approach for the given situation, and thereby reducing the risk of failure [23].

3.1.2 Stage-gate

Stage-gate, also known as Phase-gate is the most common method for developing a product. In short, the entire development process is divided into stages or phases. In order to advance to the next stage, results obtained in the current stage must be verified at decision points or gates. Hence the name Stage-gate [24]. It is highly structured and usually involves deciding on crucial specification early in the development process. Typically, the process is divided into 5 or 6 stages. Each stage covers important aspects of the design. At the gates, an assessment of the previous stage is being done with regards to information available including risk analysis, resources and so on.

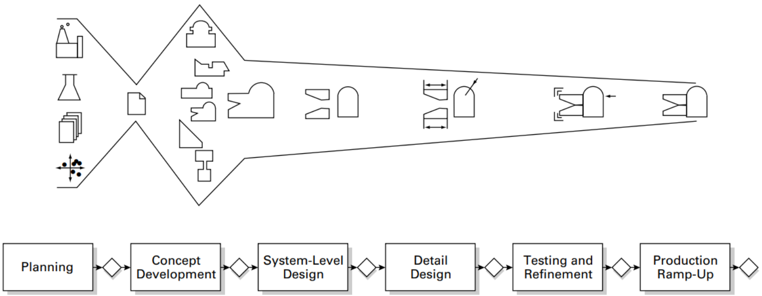


Figure 3.1: Stage-gate process, Ulrich and Eppinger [25].

One of the most famous Stage-gate models, is the one created by Karl T. Ulrich and Steven D. Eppinger (Figure 3.1).

- **Planning** - Specific plan for the upcoming stages, choosing a broad range of opportunities, and narrowing down through evaluation at the gate where only the best solutions advance.
- **Concept development** - Requirements and necessities from the target market are identified, and alternative concepts are created and evaluated, the most promising concept is chosen with a description of its functions, form, features, and specifications.
- **System level design** - Architectural design through sketches are developed along with key components and dimensions of the final product.
- **Detail design** - Specific geometry and material along with specific components from suppliers are introduced. Documentation with regards to strength, the price of material and components are created. The design is reviewed in a highly detailed Computer-aided design (CAD) assembly with all components present.
- **Testing and refinement** - Testing is done through prototyping, Computer-aided engineering (CAE) and other tools.
- **Production ramp-up** - Focuses on using the intended production system, and training workforce with the intent of creating a lean production.

Stage-gate is a highly favorable methodology for managers and leaders, as they can keep a short leash on the project's development, and stop or kill the process if demands are not met at the gates. Downsides are problems related to late discoveries, often resulting in design loops. A design loop causes the development process to jump back one or more stages, as requirements at the gate are not attained. This costs companies both time and resources, and in worst cases, a complete redesign is unavoidable [26]. The process also has an unwanted constraining effect on innovation. As a response to this, flexible product development was born [27].

3.1.3 Flexible product development

According to the three Russian professors A.I Podgoranaya, S. I. Gurdina and S.G. Avidonina (2015), *Flexibility is considered to be the first-order condition for an enterprise innovative development* [28]. By making product development a more varied activity, and developing flexible designs open for modifications, will have a more beneficial outcome for a company's capability of responding to a changing market. With a focus on design-, function, and application of a concept, flexibility enhances the team's ability to generate and respond to new information for a longer portion of the development cycle [29]. How to do so is greatly dependent on early feedback from current product performance through co-design with customers along with greater time and resource investments through the development phase.

Preston Smith stated that flexibility is the key-word in this strategy, and the later you are able to make changes in your design, the more flexible the process becomes [30]. As opposed to Stage-gate, designers are instructed to keep crucial parts in the design open for modification as long as possible without compromising other criteria of the design. This could, for instance, be its function, weight or size. One of the dangers when focusing too much on flexibility is that the design becomes too adaptable to changes, which again cause problems in decision making, and may result in a waste of time and money. Smith suggests that flexibility should only be applied on places where innovation is needed, to keep the process going.

3.1.4 Set-based design

Set-based design is a practice that locks certain elements of the design while keeping others open to adjustments and changes. By doing so, the method allows designers to explore and identify several solutions, weighing them against each other, and avoid bad choices. A final decision is made only when the solutions has been validated through proper simulations and/or simple testing [30, 31].

Set-based design defines a set of solutions running parallel to each other (Figure 3.2). Each solution is explored and analyzed, gradually narrowing down the number of solutions through so-called learning points. Each learning point is a step closer to one optimal solution. When the final solution is established, it is locked, meaning it does not change unless absolutely necessary.

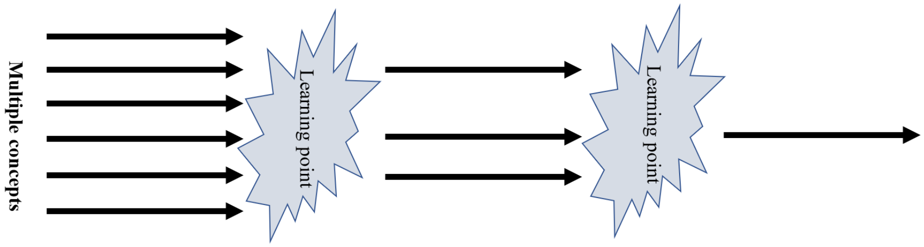


Figure 3.2: Model of Set-based design.

3.1.5 Iterative development

An iterative development process (Figure 3.3) focuses on repetitions of an initial design. It is a cyclic process, where the overall goal is to gain as much knowledge as fast and early as possible. The process involves front-loading, which means using a lot of resources in the early stages of the development. The iterations help to avoid late learning and expensive design re-loops, typically experienced in more linear approaches, like in Stage-gate. On the downside, the process is difficult to manage, and keeping track of progress is hard. To help guide the progress forward, a project control checklist is used [32].

Each iteration involves planning, designing, building, testing and reviewing. The result of each repetition is short intensive bursts of learning, gradually narrowing down to the most ideal design. With information gained through the iterations, the development team can stay flexible and act on unforeseen changes, which is extremely valuable for further development [33, 34].

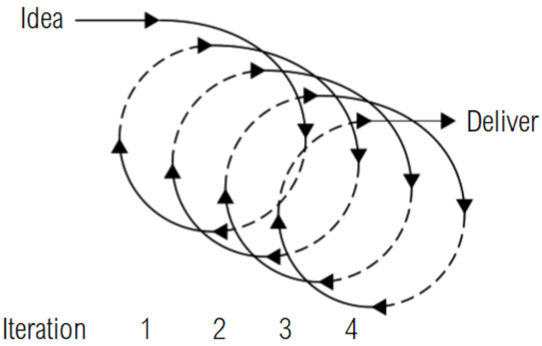


Figure 3.3: Model of Iterative development, P. G. Smith [30].

3.2 Prototyping

Sometimes having a comprehensive knowledge of how we design, is not enough to keep the development process going. The famous Albert Einstein once said: “Whats the difference between theory and practice? In theory, they are the same. In practice, they are not” [35]. A great tool to help with creating physical approximations of what we are designing is prototyping.

The term prototyping has many different definitions. One can argue that a simple brick is a prototype, it just comes down to how it is used. The brick can, for example, be used to represent weight or size of a future design. As a consequence, a whole vocabulary has been established to define the different kinds of prototypes. The most important ones are:

- **Visual prototype** - Exhibits appearance and size of the expected design.
- **Proof of concept prototype** - Exhibits some vital, but not all functions of the expected design.
- **Working prototype** - Exhibits practically all the functions of the expected design.
- **Functional prototype** - Exhibits all functional and visual functions of the expected design, but made with different techniques.

Stephanie Houde and Charles Hill define a prototype as means of exploring and expressing design [36]. In other words, it uses a combination of methods to give an idea, a physical or visual form and thereby lets the designers evaluate solutions and generate more knowledge of the design. The design gets to ”practice being itself” [37]. By incorporating the use of prototypes either early or late in product development will help minimize design errors. They are also inexpensive and are of much help when identifying issues both in a disciplinary and cross-disciplinary field [38].

3.2.1 Rapid prototyping

Rapid prototyping is a way of generating prototypes as fast as possible with the use of computer-aided design (CAD) and additive manufacturing (3D printing). The process allows designers to create complex parts without taking difficulties of manufacturing into account and is especially a great tool for producing small parts [39].

3.3 Human modeling

Human modeling is a type of computer-aided engineering (CAE) tool. The tool can create human models, and add them into different CAD assemblies. This process is convenient for verifying designs that will interact with humans, especially with regards to dimensions and proportions. Siemens NX has an integrated tool for human modeling. This human modeling tool uses body measurements from the Anthropometric survey of U.S. Army personnel from 2012 which has a sample data population of 3922 women and 7435 men [40].

Chapter 4

Previous Work

Since the start in 2014, an apparatus for rehabilitation of whiplash patients have been developed through four master's and specialization projects. The work has mainly been concentrated on three main topics.

- **Motion platform**
  Will provide resistance against the patient's movement, to strengthen muscles in order to rehabilitate the damaged area.
- **Head mount**
  A mechanism for fixing the patients head to the apparatus.
- **Chair**
  A comfortable and stable design for the patient to sit in.

4.1 Motion platform

4.1.1 Stewart platform

The first concept of the apparatus was developed by Kristoffer Bjørnerud Slåttsveen and Sondre Frantsen Tolo, and used a Stewart platform [41] as the motion platform. Stewart platform is a closed kinematic chain robot manipulator (Figure 4.1).

Figure 4.1: Stewart platform from Slåttsveen and Tolo thesis [41].

Although the design had a great potential, there was complications regarding the robots maximum capabilities of angular displacement. Also, the platform showed concerns regarding singularities typical for closed chain kinematics (Section 2.4). As a result the design was dropped.

4.1.2 MASNAK

MASNAK was developed by Ole Jacob Berg and Østein Kavle Sunde, and is another form of closed chain robot, consisting of a linear actuator controlled multi-joint mechanism [42]. It consists of two serially connected five-joint mechanisms and allows for free movement in one plane. The platform uses four linear actuators which would act passively against the movement of the patient (Figure 4.2).

Despite using linear actuators instead of a weight system, it did restrict the patient to move around the axes of the apparatus, and not the cervical joints. The initial position of the patient would have to rotate $\mp 90^\circ$ to do sideways motions. The design was dismissed because it proved too simple and similar to the current MCU.

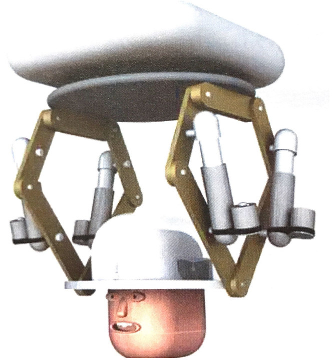


Figure 4.2: MASNAK platform from Berg and Sunde thesis [42].

4.1.3 Cable robot

Through the Thomas L. Gælok and Michelle Strand thesis [43], investigations were done using a cable robot as the motion platform. The head of the patient is fixed inside the center of a cube (Figure 4.3). Each corner has a pulley with a cable going through. Each cable is then attached to a winch, and each winch has a sophisticated control unit. The winches will handle the different cable lengths, forces and give appropriate resistance against the patient's movements.

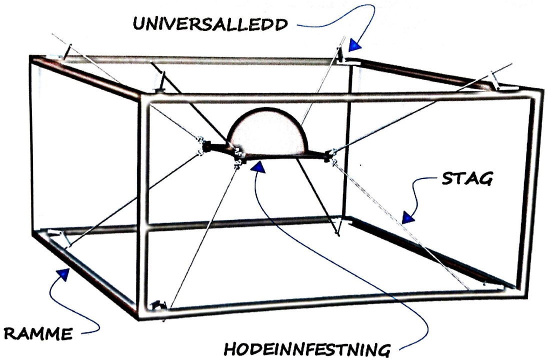


Figure 4.3: Cable robot platform from Gælong and Strand thesis [43].

The Cable robot would have made it all the way to a physical prototype if it was not for the complexities of using highly advanced winches to facilitate the rehabilitation. Winches with a force feedback system had at the time a price tag of 10 000 Euros each, which meant that the prototype would become way too expensive.

4.1.4 Robot arm

The latest and most promising concept was using a robotic arm to serve as the motion platform. During Gælok and Strand's project period, a new type of robot arm was introduced to the market. The Panda robot developed by a startup company called Franka Emika (Figure 4.4). It is the first robot in its price range with a substantial and sophisticated feedback system provided by advanced sensors located in each joint of the robot. The design potentially opened the possibility of using a robot arm as the motion platform.

Figure 4.4: Panda by Franka Emika [44].

The patient would be connected to the end effector of the robot arm by an appropriate head mount. When the physiotherapist has located the damaged region of the neck, the robot arm will be programmed to act passively against the patient's movement. The force of the arm can be adjusted depending on the severity of the patient's injury. Virtual walls can also be created in the software, thus blocking unwanted motions, and thereby guiding the correct motions of the patient. This makes arranging different rehabilitation programs for the therapist much easier, as the proper motions can be taught to the patients by the robot.

The price of the robot including accessories is 9 900 Euros, and it comes with software for easy programming. The robot has 7 degrees of freedom, which reduce problems regarding singularities (Section 2.4) and increases the possibilities for the task space. Physical tests were conducted at a company visit during Brattgjerd's specialization period, and the results were promising. However, further examination of both the physical and theoretical capabilities are required.

4.2 Head mount

The head mount serves as the end effector of the robot arm and provides a suitable fixture for securing the patients head. Through previous projects, several innovative and smart solutions have been investigated. Gælok and Strand reviewed the most recent and auspicious solutions. A total of 10 concepts were developed and tested with a focus on comfort, size range, stability, reliability, and more. By the ten concepts, two showed the most potential, padded and inflatable head mount.

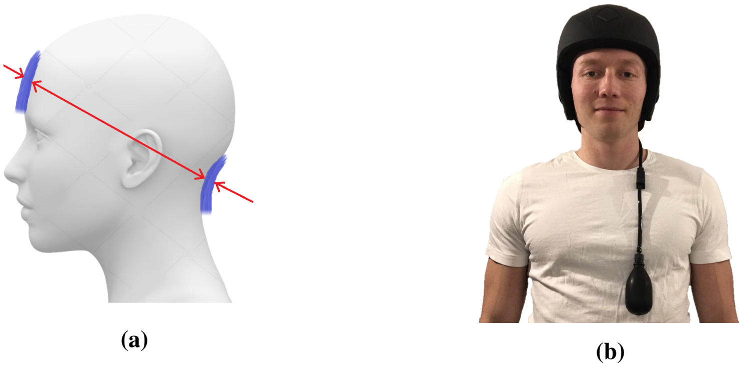
4.2.1 Padded head mount

The design uses pads of different material as a cushion to symmetrically press against the head of the patient. The pads were tested in different sizes and would be pressed against appropriate areas to make a rigid connection. Gælok and Strand made a wooden test rig, to test different types of padding. The designs focused on comfort, minimal slack, and adaptability to different head sizes. Air-pillows, cellular rubber, gel, polyfoam, and plasticine were all tested. The best result was revealed to be the plasticine padding. It gave little slack in all directions and was reasonably comfortable.

4.2.2 Inflatable head mount

The second promising concept involved a hardhat as a rigid outer shell, with one or more inflatable elements inside. The patient would place his/her head inside the mount, and the elements would consequently be filled with air. Upon inflation, they would start pushing towards the patient's skull with an equal and symmetric force.

The solution fits several different head sizes. A bigger head, results in less inflation, compared to a smaller head. Through prototyping, two types were tested. One design had one inflatable element consisting of an inner tube and a hardhat. The second one had two inner tubes, attached to two corresponding rigid side elements. Results showed that one single element was the best alternative. The design was comfortable, but some slack was noticed when doing the different head movements.



(a)

(b)

Figure 4.5: Anchor points (a) and prototype of Etto twister with inflatable neck pillow (b) (Appendix H).

During the specialization project of Brattgjerd (Appendix H), a dialog was established with one of Scandinavia's biggest helmet producers, Etto. The development team shared their knowledge of giving their helmets a stable and secure fixture. The key lies in using the area on the skier's forehead and back of the head as anchor points when developing the fixture.

A prototype was made using an Etto helmet called Twister (Figure 4.5), which has a rigid outer shell of Acrylonitrile butadiene styrene (ABS) material. The helmet also covered the ears, which is favorable for a decent sideways fixture. An inflatable neck pillow was bought and used as the element, with a bulb pump for inflation. The element was installed on the inner backside of the helmet, thus pressing the patient's forehead towards styrofoam pads inside the helmet, upon inflation. The prototype was reasonably comfortable, but was a bit too big and did not fit into the helmet very well. It was also a bit tiring on the ears after about 10-15 minutes of use.

4.2.3 Mounting mechanism

The mounting mechanism is the component used for connecting the helmet to the robot arm. It was essential that the mounting mechanism would be easy and quick to use, with zero looseness tolerated. Through Brattgjerd's specialization project (Appendix H), a total of five designs were evaluated.

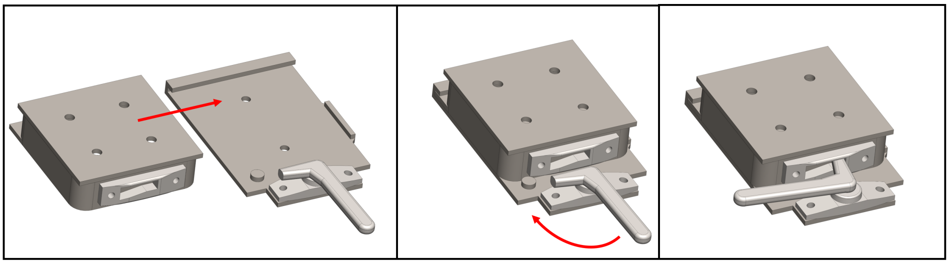


Figure 4.6: Mounting mechanism for head mount (Appendix H).

The best solution used a slide and lock mechanism. The mechanism works as shown in Figure 4.6. One part is slid into the other and locked with a window latch. During Brattgjerds specialization project, the solution was manufactured (Figure 4.7). The mounting mechanism requires a flat surface to connect to the helmet. A 3D-printed mounting shim was made to create a flat surface. The holes from the goggle clip at the back of the helmet were used to fasten the shim.

Figure 4.7: Manufactured mounting mechanism for head mount (Appendix H).

4.3 Chair

The chair is a configuration for the patient to sit in and should provide a comfortable and secure layout. It should also have an appealing look and feel of quality. In 2015, Marius Kirkeeide wrote his thesis investigating what type of chair would be adequate for the apparatus [45]. His work resulted in two different concepts. The first one is a seated system, and the second one is a more modular system open for sitting or standing rehabilitation.

4.3.1 Seated design

The seated design (Figure 4.8) resembles a standard chair, except that it is highly adjustable to fit any given body shape and form.

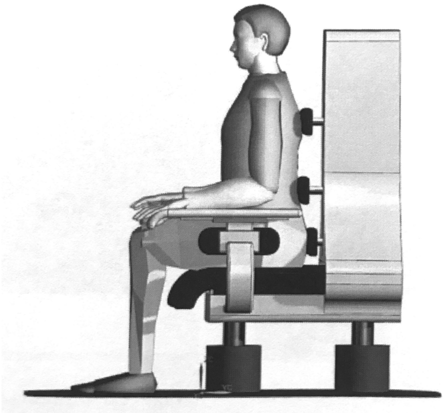
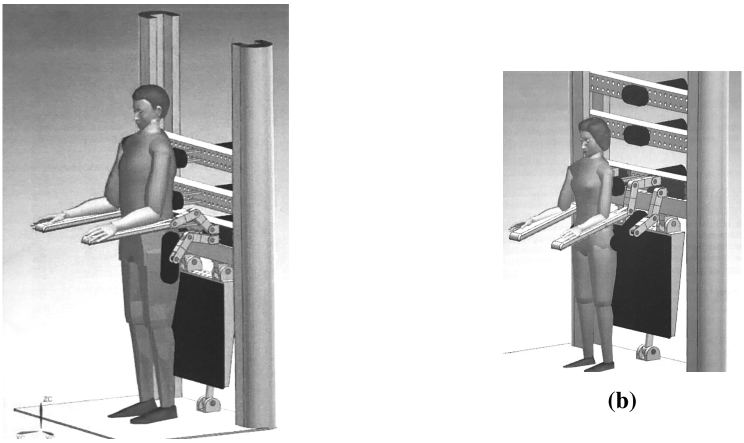


Figure 4.8: Seated concept of apparatus, Kirkeeide thesis [45].

4.3.2 Modular design

The modular design (Figure 4.9) opens for the possibility to undergo the rehabilitation training while the patient is standing. It was a request made by FPMC, as an opportunity to look into. The standing configuration provides the therapist with more flexibility when it comes to setting up an advanced recovery training program. If the seated version is desired, a foldable chair at the bottom can be utilized. On the downside, the design of the foldable chair prevents the two uppermost backrests to be lowered enough to reach persons of shorter stature.



(b)

(a)

Figure 4.9: Modular concept of apparatus. Standing rehabilitation for patients of higher (a) and shorter (b) stature, Kirkeeide thesis [45].

Chapter 5

Current Concept

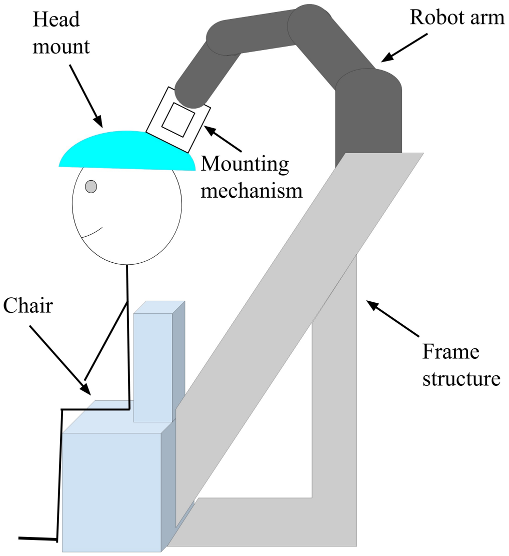


Figure 5.1: Current concept components.

This chapter will present the development process of the motion platform (robot arm), head mount, chair and frame structure (Figure 5.1). Each component of the apparatus is given its own section. Each section contains a short summary, requirements, method, concept, development, evaluation and a final summary. The requirement tables are repeated in the evaluation section, to give a clear overview of which requirements that have been assessed.

5.1 Motion Platform

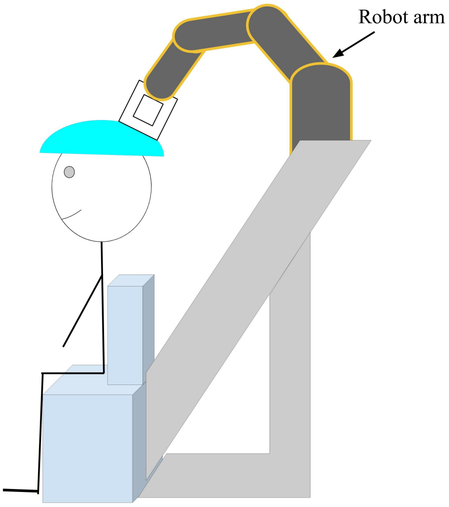


Figure 5.2: Robot arm component of current concept.

The motion platform (Figure 5.2) is the component of the apparatus that provides resistance against the patient's movement. The latest discovery recommended the robotic arm Panda from Franka Emika as the motion platform. The feasibility of using Panda as a motion platform is evaluated by simulating its workspace and load capacity. All simulations showed that the robot has sufficient load capacity, but the robot fails to fully deliver the required training space when using the current mounting position.

5.1.1 Requirements

Product requirement specification

Table 5.1: Motion platform - product requirement specification.

Requirement	**Specification**	**Crucial**	**Beneficial**
Functional requirements	—	—	—
Motion/training space	Forward: 75° Backward: 55° Sideways:±50° Rotation: ±80° Figure 5.3		X
Accuracy	Translation: $\pm 3\,\mathrm{mm}$ Rotation: ±2°		
Diagnostic through neutral motion	Analysis of patients motion amplitude	X	
6 Degrees of freedom		X	
Effortless establishment of training programs			X
Virtual walls			X
Force control		X	
Load capacity	$>20\,\mathrm{N}$ forward/backward and sideways $>10\,\mathrm{N\,m}$ Rotation	X	
Smooth motion	Steady motion and speed	X	
Assisting software		X	
Database for each patient	Storage of individual rehabilitation programs for each patient	X	
Rachability	$> 1000\,\mathrm{mm}$	X	
Weight	15-30 kg		X
Hygenic	Easy to clean		X
Safety requirements	—	—	—
Emergency button	Accessible for patient in case of distressing situations	X	
Automatic stop	Stop when irregularities occur during rehabilitation	X	
Certified for intended purpose		X	

Motion/Training space

The main motions of rotation are backward/forward, sideways and rotational motion (Figure 5.3). These paths equals rotation around the three main axes X_0, Y_0 and Z_0. Note that the main axes equals the reference frame at the base of the robot. Preferably the motion platform should not be restricted to only rotate around these axes, but also a combination of these.

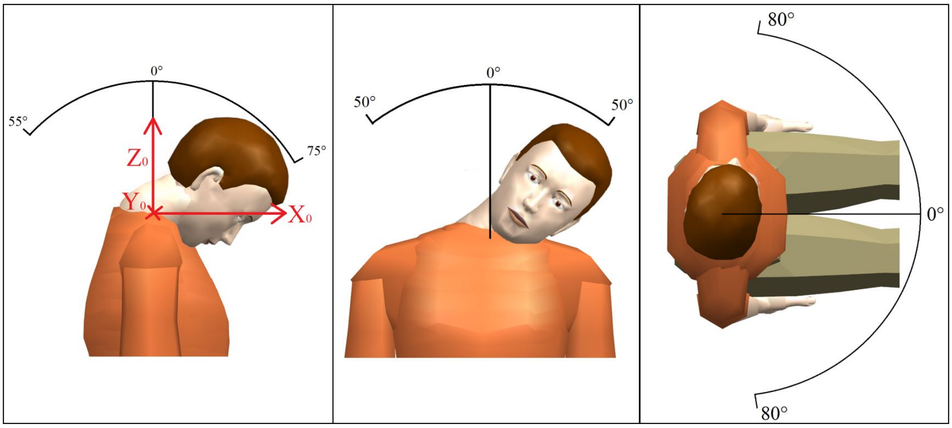


Figure 5.3: Motion/Training space. From left: backward/forward, sideways and rotational motion.

Table 5.2: Motion platform - user requirement specification.

Requirement	**Specification**	**Crucial**	**Beneficial**
Usage requirements	—	—	—
Good user interface	For both patient and physiotherapist		X
Sturdy and comfortable motion	Minimal slack and distressful motions	X	
Design requirements	—	—	—
Soothing color			X
Non intimidating		X	
Hygenic	Looks hygenic and practical colors for detecting tarnish		X
Feel of quality	Looks and feels like a quality product		X

5.1.2 Concept

Past research and concepts have concluded that a robotic arm is a good solution to fulfill the requirements needed for the motion platform. The robotic arm Panda from Franka Emika (Figure 5.4), has a very reasonable price and advanced sensor technology, which makes it a good candidate for this purpose. The autumn of 2017 a visit to Munich was made to test if the robot could achieve the requirements. A quick overlook on the robot made it look promising, and the decision to buy one for further testing was settled. The funding was not acquired in time for this thesis. As a solution, a computer model was made to evaluate the robotic arm. The evaluation in this chapter focuses on whether or not the robot arm is strong enough to perform the desired task, and if the task space covers the training space required for an optimal whiplash rehabilitation.

Figure 5.4: Panda by Franka Emika, picture from visit to Munich (Appendix H).

5.1.3 Development

Model

Panda is a robotic arm with 7 DoF consisting of only revolute joints. The Denavit-Hartenberg convention was chosen to model the robotic arm. The DH-parameters of Panda (Figure 5.5) were available in the documentation from Franka Emika [46].

Much research was done into choosing a platform to model the robotic arm. It exists a lot of different framework for DH-parameters, but because of the author’s solid knowledge in Matlab, along dialogues with cybernetics student Shahrukh Khan, the Peter Corke robotic toolbox was chosen [47]. This toolbox is a free, open-source package for Matlab. The toolbox is easy to use with a lot of documentation, mathematical functions and plot options for DH-parameters.

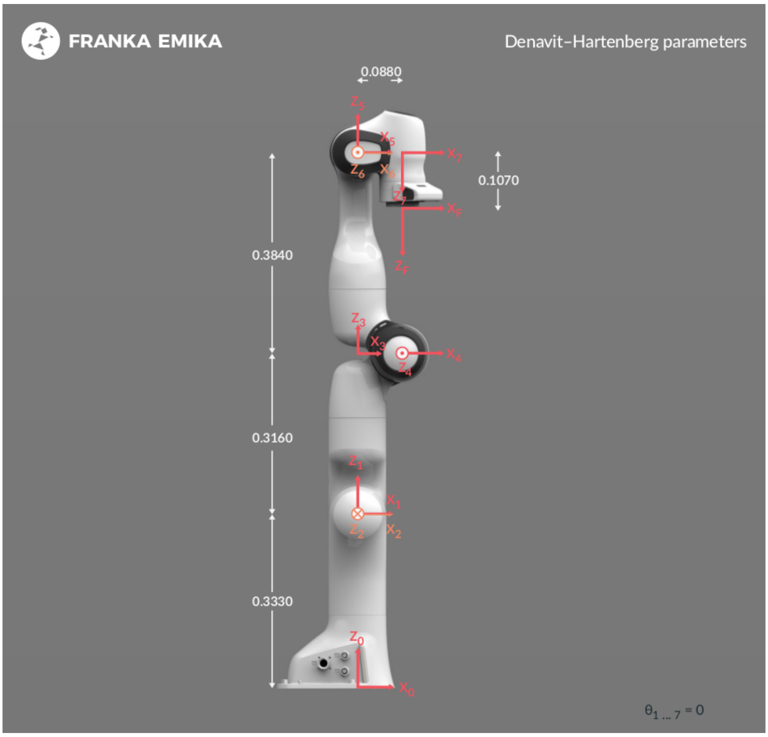


Figure 5.5: Panda with reference frames placed with Denavit-Hartenberg convention (dimensions in meters) [46].

To build the model, technical specifications of the robot were needed. Franka Emika would unfortunately not disclose any specifications other than the public information given in the technical data sheet (Appendix A) and a web page containing some extra information [46]. The available specifications were limited to the DH-parameters, angle limits, total mass and all geometrical dimensions in the CAD file (Appendix A). That is, all the kinematic parameters, but none of the dynamic.

To create a dynamic model the inertia matrix and mass for each link are needed. To create a dynamic model, a simplified and exaggerated approximation of the arm was made (Figure 5.6). Each link was simplified to a cube and several cylinders with uniform mass. The measurements of the approximated cylinders are based on dimensions collected from the CAD models provided by Franka Emika.

The full weight of the robot is $18\,\mathrm{kg}$. The main weight of the robot is the seven motors located in each joint. The first four motors are stronger, with a torque of $87\,\mathrm{N\,m}$ while the other three have a torque of $12\,\mathrm{N\,m}$ (Appendix A). Since the first motors are more powerful than the rest, they are assumed to weight more. The approximation of the first four links was set to a weight of 3 kg and the other four links to 2 kg, which become a total weight of 20 kg. This results in an exaggerated model weighting 11% more than the actual robot. Finally, the inertia matrix for each link assuming uniform mass was calculated and added to the model.

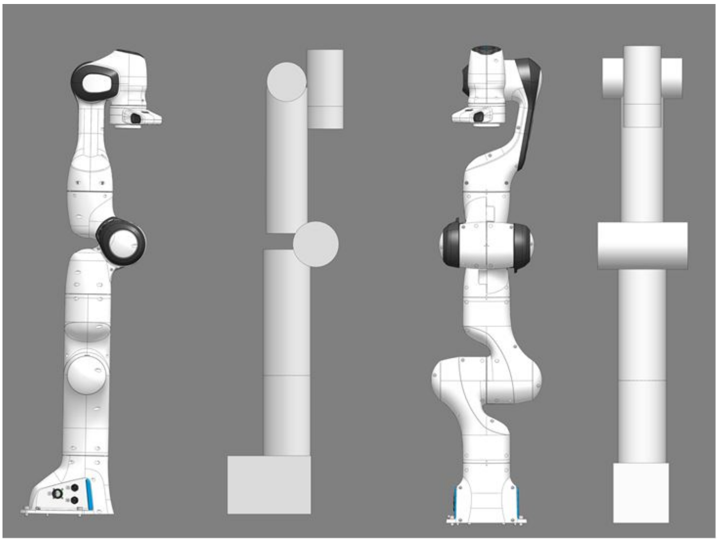
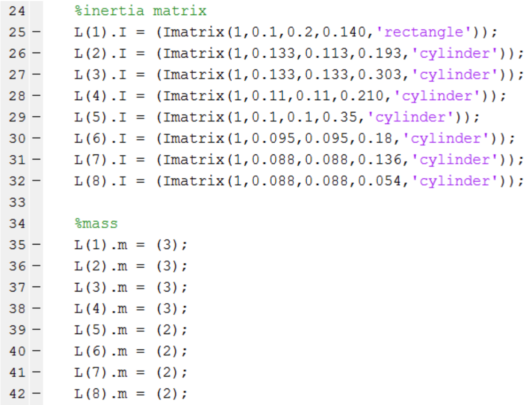


Figure 5.6: CAD assembly of Panda next to the simplified model used for calculations.

Each of the links is modeled in Matlab using the link object (L(x) Figure 5.7), from the Peter Corke toolbox. The required parameters are then added to each link. Inertia matrix (L(x).I) and mass (L(x).m) are added to the model by setting the properties of the link objects. Imatrix is a function created by the author that calculates the inertia matrix based on width, breadth, height, and type of object (rectangle or cylinder) (Appendix G).

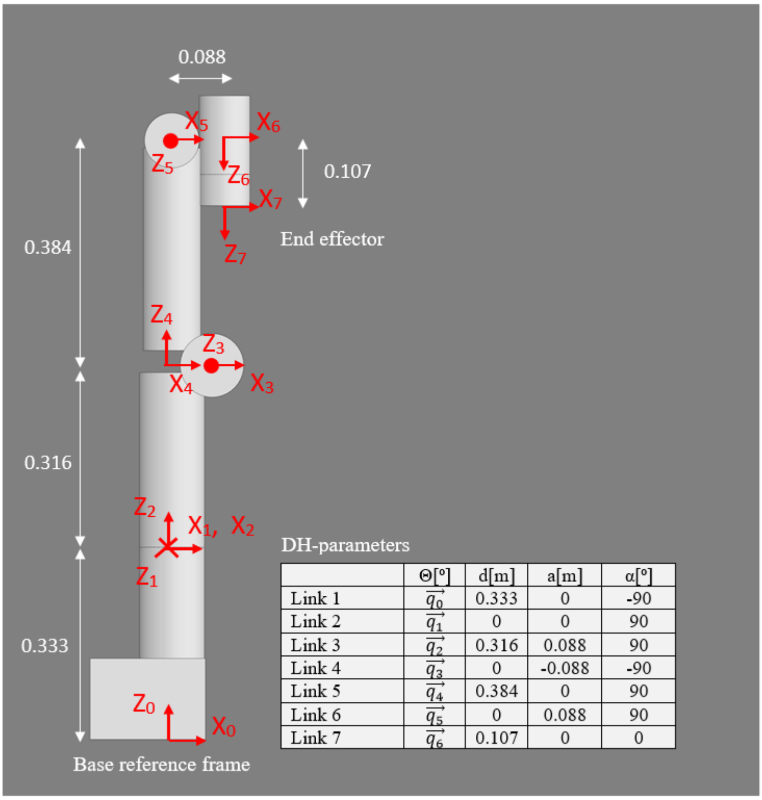


```
%inertia matrix
L(1).I = (Imatrix(1,0.1,0.2,0.140,'rectangle'));
L(2).I = (Imatrix(1,0.133,0.113,0.193,'cylinder'));
L(3).I = (Imatrix(1,0.133,0.133,0.303,'cylinder'));
L(4).I = (Imatrix(1,0.11,0.11,0.210,'cylinder'));
L(5).I = (Imatrix(1,0.1,0.1,0.35,'cylinder'));
L(6).I = (Imatrix(1,0.095,0.095,0.18,'cylinder'));
L(7).I = (Imatrix(1,0.088,0.088,0.136,'cylinder'));
L(8).I = (Imatrix(1,0.088,0.088,0.054,'cylinder'));

%mass
L(1).m = (3);
L(2).m = (3);
L(3).m = (3);
L(4).m = (3);
L(5).m = (2);
L(6).m = (2);
L(7).m = (2);
L(8).m = (2);
```

Figure 5.7: Matlab code for including mass and inertia matrix to the model.

There are different conventions for setting the DH-parameters. The Peter Corke toolbox and Franka Emika operate with slightly different conventions. The parameters from Franka Emika were modified to fit the toolbox. The DH-parameters used in the model (Figure 5.8) are the same as described in section 2.4. No measurements were changed, and the kinematics are preserved.

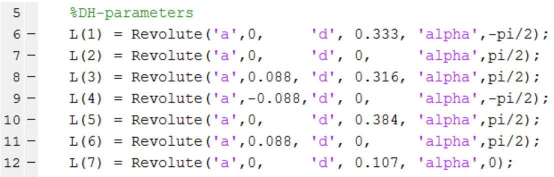


DH-parameters

	Θ[°]	d[m]	a[m]	α[°]
Link 1	$\overrightarrow{q_0}$	0.333	0	-90
Link 2	$\overrightarrow{q_1}$	0	0	90
Link 3	$\overrightarrow{q_2}$	0.316	0.088	90
Link 4	$\overrightarrow{q_3}$	0	-0.088	-90
Link 5	$\overrightarrow{q_4}$	0.384	0	90
Link 6	$\overrightarrow{q_5}$	0	0.088	90
Link 7	$\overrightarrow{q_6}$	0.107	0	0

Figure 5.8: Simplified model of Panda with the reference frames and DH-parameters.

All the joints of Panda are revolute. The DH-parameters were included in the model using the Revolute function from the toolbox (Figure 5.9).



```
%DH-parameters
L(1) = Revolute('a',0,     'd', 0.333, 'alpha',-pi/2);
L(2) = Revolute('a',0,     'd', 0,     'alpha',pi/2);
L(3) = Revolute('a',0.088, 'd', 0.316, 'alpha',pi/2);
L(4) = Revolute('a',-0.088,'d', 0,     'alpha',-pi/2);
L(5) = Revolute('a',0,     'd', 0.384, 'alpha',pi/2);
L(6) = Revolute('a',0.088, 'd', 0,     'alpha',pi/2);
L(7) = Revolute('a',0,     'd', 0.107, 'alpha',0);
```

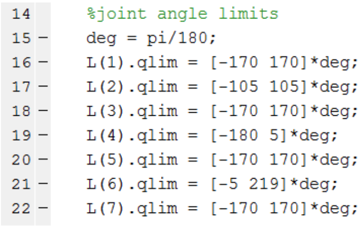
Figure 5.9: Matlab code for adding the DH-parameters to the model.

Detailed information on the motors used in the Panda are confidential, but they are most likely modified brushless direct-current (BLDC) electrical motors. For most electrical motors of this type, the friction coefficient is related to the motors bearing friction, and can be neglected [48]. Therefore, a friction coefficient was not added to the model.

Finally the joint position limits (Table 5.3) were added to the model. The limits (in radians) were added to the model using the Qlim function of the toolbox (Figure 5.10).

Table 5.3: Joint position limits for Panda

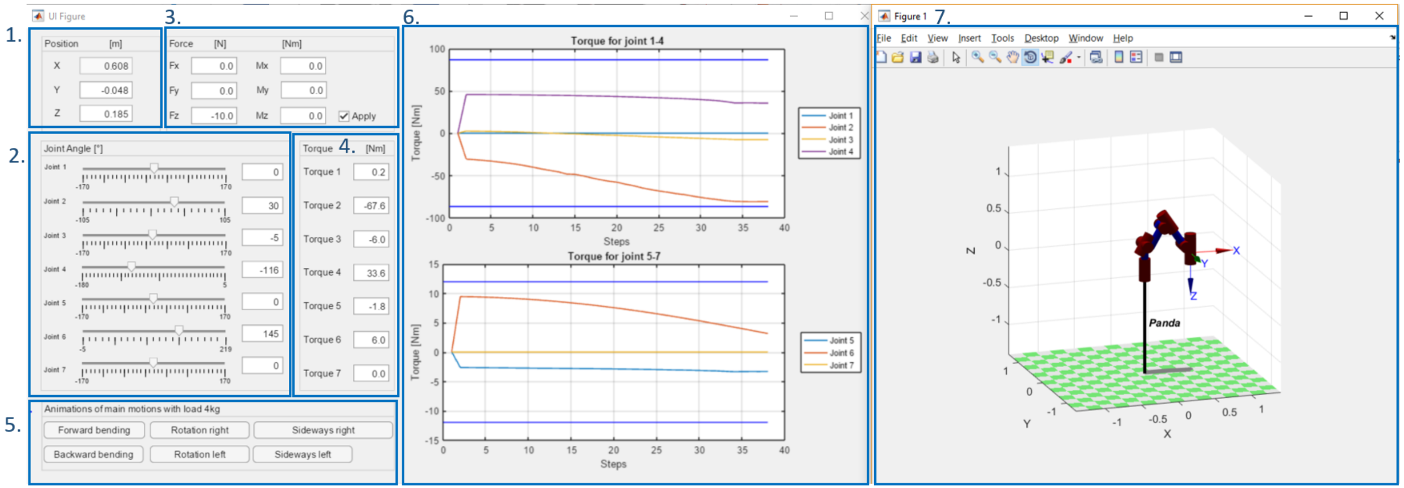
	Min [°]	Max [°]
Joint 1	-170	170
Joint 2	-105	105
Joint 3	-170	170
Joint 4	-180	5
Joint 5	-170	170
Joint 6	-5	219
Joint 7	-170	170



```
%joint angle limits
deg = pi/180;
L(1).qlim = [-170 170]*deg;
L(2).qlim = [-105 105]*deg;
L(3).qlim = [-170 170]*deg;
L(4).qlim = [-180 5]*deg;
L(5).qlim = [-170 170]*deg;
L(6).qlim = [-5 219]*deg;
L(7).qlim = [-170 170]*deg;
```

Figure 5.10: Matlab code for adding joint limits to the model.

In summary, the model consists of DH-parameters, eight links modeled of one cube and seven cylinders of universally distributed mass, inertia matrix for each link and angle limitations for each joint (Appendix G).



Position [m]
X 0.608
Y -0.048
Z 0.185

Force [N]
Fx 0.0
Fy 0.0
Fz -10.0

[Nm]
Mx 0.0
My 0.0
Mz 0.0
☑ Apply

Joint Angle [°]
Joint 1 (-170 – 170) 0
Joint 2 (-105 – 105) 30
Joint 3 (-170 – 170) -5
Joint 4 (-180 – 5) -116
Joint 5 (-170 – 170) 0
Joint 6 (-5 – 219) 145
Joint 7 (-170 – 170) 0

Torque [Nm]
Torque 1 0.2
Torque 2 -67.6
Torque 3 -6.0
Torque 4 33.6
Torque 5 -1.8
Torque 6 6.0
Torque 7 0.0

Figure 5.11: Interface for computer model.

Interface

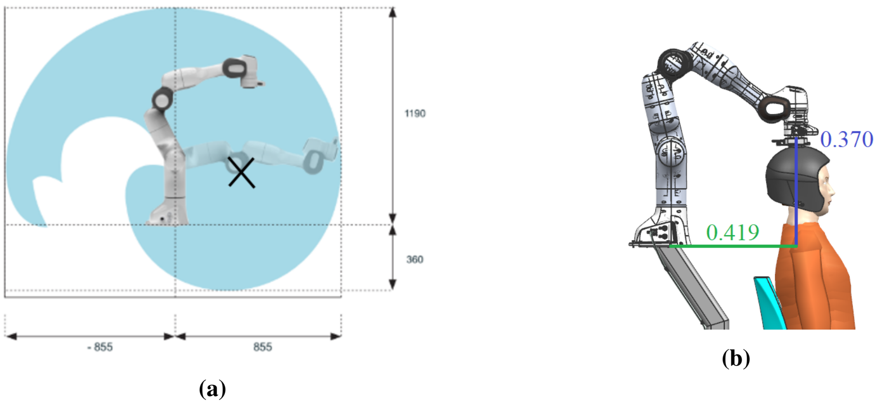
It was necessary to make the robotic model as user-friendly and re-usable as possible. It was decided to make an interface for the model. The interface (Figure 5.11) was made from scratch in Matlab using App Designer (Appendix G). More screen shots of the interface can be found in Appendix B. The interface consists of several parts:

1. **Position** - This panel shows the position of the TCP explained in the main reference system.
2. **Sliders for joint angles** - These sliders make it possible to change the angle in each joint, to place the robot in the desired position. The angle value can also be changed by inserting the value in the edit field. It is not possible to select a value outside the joint limits.
3. **Force** - This panel adds a force or moment to the end effector. These forces are explained in the main reference system. The force is first inserted, and then the apply button is ticked off to add the force. Note that the program runs slower, because of the added calculations when forces are applied.
4. **Torques** - When a force is applied to the end effector, the resulting torque in each joint are calculated and shown in the boxes.
5. **Animations** - The buttons starts an animation of the robot in one of the main motion paths.
6. **Plot** - The torque in each step of the animations are plotted in these fields, to show that the torques created from the motion do not exceed the joint limits. The top plot shows the first four joints with limits of $87\,\mathrm{N\,m}$ and the bottom shows the last three with limits of $12\,\mathrm{N\,m}$.
7. **Robot** - The right plot is created by the toolbox and moves when the buttons on the left side are used.

Initial training space position

Because of Panda's limited task space, it was important to place the initial position of the patient's head in a position that allowed for the best utilization of the task space. Previously the connection between the helmet and robot arm was at the back of the helmet (Section 4.2.3). It was discovered through simulations, that the previous mounting should be moved from the back of the helmet to the top of the helmet. The reason for this was the limitation of -5° to 219° in joint 6. With the placement on the top, the helmet is placed in the middle of joint 6's angular displacement allowing greater use of the angle space.

When the mounting of the end effector was settled, the position was placed in the middle of the task space, to allow for the greatest reach in each direction (Figure 5.12a). This resulted in the initial position $\begin{pmatrix} 0.419 & 0 & 0.370 \end{pmatrix}$ (Figure 5.12b).



(a)

(b)

Figure 5.12: Initial position of head marked in the task space of Panda (a) [46]. Position of the head when seated in the apparatus (b).

Training space and motion space

The request from FPMC is to have the possibility to rotate in any plane. Validating all the infinite number of planes would be impossible. Therefore, rotation around the three principal axes (Figure 5.13), were selected as test planes. Rotation around these axes corresponds to backward/forward, sideways and rotational motion demonstrated in Figure 5.3. If the robot can manage these paths, it should also be capable of operating in combinations of these.

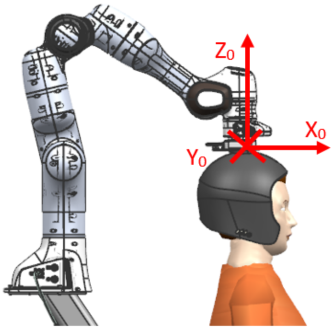


Figure 5.13: The main axes of rotation explained in the base reference system.

The evaluation of the paths was divided into three steps.
1: A physical test of the forces conducted by the patient on the robot.
2: Video analysis of the motion path.
3: Kinematic and dynamic analysis in Matlab with the path obtained from the video analysis.

Physical force experiment

A test set-up where the force could be measured dynamically while the patient is moving would be ideal. This would require much work and not necessarily increase the accuracy when the model already is a rough approximation. The test was simplified to measure max load in a static position at the start of the path. This load would subsequently be used throughout the whole path, which gives a simulated worst-case scenario for verification.

Rotation around the y- and x-axis was tested by attaching a baggage weight to the helmet, then testing forward/backward and sideways motion (Figure 5.14a). Brattgjerd and Festøy were used as test persons. Both tried to push as hard as possible to measure max load. Brattgjerd manages to apply $6\,\mathrm{kg}$ while Festøy reached $5\,\mathrm{kg}$. The average training load was measured around $2\,\mathrm{kg}$. Therefore, the load of $4\,\mathrm{kg} \approx 40\,\mathrm{N}$ was chosen as the test load for the computer model.

(a) **(b)**

Figure 5.14: Test set-up for loads during rehabilitation training. Sideways rotation with baggage weight (a). Rotational motion with a torque wrench (b).

Rotation around the z-axis was tested with a torque wrench (Figure 5.14b). Brattgjerd applied full force and reached a maximum torque of $10\,\mathrm{N\,m}$. The patients have injured necks, in contrast to Brattgjerd that has a powerful neck, and it is highly doubtful that they will be able to exceed this torque.

Video analysis of motion path

The trajectory of the motion paths was needed to simulate the motions paths in Matlab. A free tool called Tracker was used for this purpose [49]. Tracker allows tracking of a moving object in a video. By analyzing videos of the movement, the trajectories for each motion was found.

Test set-up (Figure 5.15): The test person was placed in a regular chair in front of a white background. A post-it note in contrast color with a reference frame was placed on top of the helmet in the position where the TCP would be. A video was then taken of all the different motions.

Figure 5.15: Video set-up for forward/backward motion.

Three videos were analyzed in Tracker, forward/backward, sideways and rotational motion. Tracker can auto track an object in a movie. The Origo of the reference frame on top of the helmet was chosen as the reference point. The output is data points along each axis in the video, resulting in the exact path of the training motion. In addition to the coordinates of the path, the orientation of the reference frame was needed. Tracker does not have the ability to auto track a vector. The angle of the reference system (ϕ) was measured at the beginning and end, and simplified to a linear interpolated between the two points. In summary, the data set from Tracker contains three vectors, two for motion coordinates and one for the angle.

Kinematics

The output from Tracker, motion path and orientation, were then imported to Matlab to compute the kinematics. The coordinate system used in Tracker did not correlate with the one used in Matlab. As a result, the data points were transformed into the main reference frame of the robot and given a correct start position of the movement. Based on the position and orientation of the TCP (task space) the joint angles (joint space) was found using inverse kinematic 2.4.

The inverse kinematic function SerialLink.ikcon [50], from the toolbox was used for calculating the joint space. Ikcon is a numerical inverse kinematic function taking joint limits into account. The function uses the robot's end effector pose, T (4x4), and returns the joint coordinates (1xN) corresponding to T [50]. As explained in subsection 2.4, one pose in the task space can have several solutions in the joint space. As a consequence, it is advisable to also include assumed joint coordinates as input because Ikcon is a numerical inverse kinematic and uses the inserted joint coordinates as a start point for the numerical solution.

Including assumed joint coordinates reduces the complexity and calculation time drastically. Besides, this ensures that the elbow of the robot is in the correct upward position and not downward, thus resulting in a collision with the patient. After the joint angles were found using inverse kinematic, direct kinematic was used to find the motion path the robot would follow based on the joint angles. The path obtained by Matlab fitted the data points from Tracker with high accuracy (Figure 5.16).

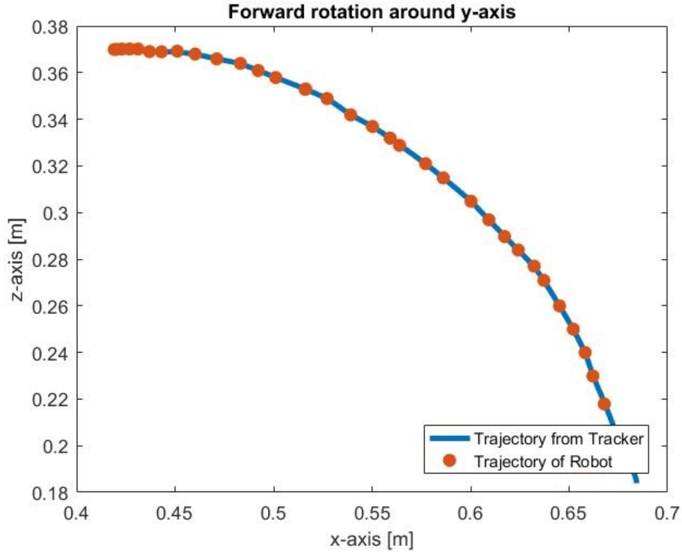


Figure 5.16: Comparison of the path from Tracker vs. the computed motion from Matlab, when performing forward bending.

Dynamics

The dynamics were calculated using the SerialLink.rne function from the Peter Corke toolbox [50]. SerialLink.rne is an inverse dynamic function (Section 2.4). It returns the torque in each joint related to a force or moment in the end effector. For rotation around the X_0- and Y_0-axis, the force was simplified to a concentrated load of $40\,\mathrm{N\,m}$. The direction of the force is modeled by letting the force be dependent on the angle ϕ of rotation around the base frame (Figure 5.17, Equation 5.1). The torque related to the rotation around the Z_0-axis were modeled as a torque of $10\,\mathrm{N\,m}$ around the Z_0-axis.

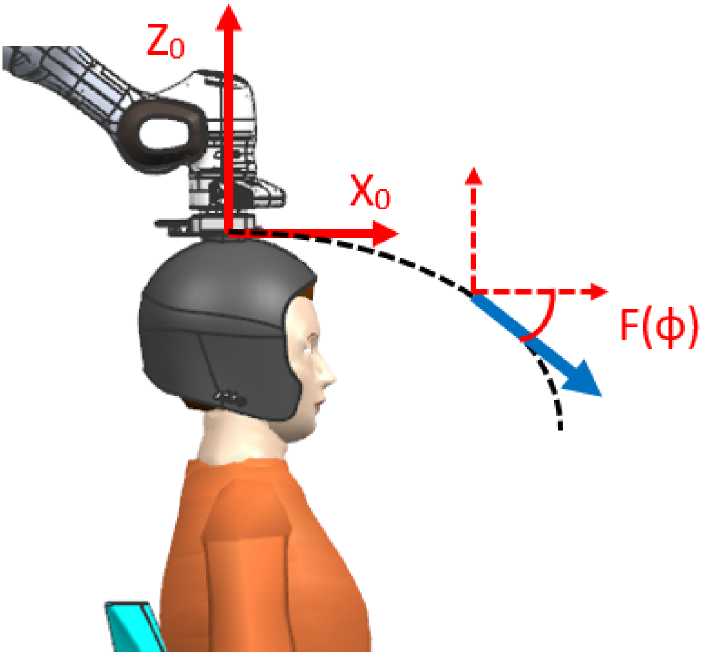
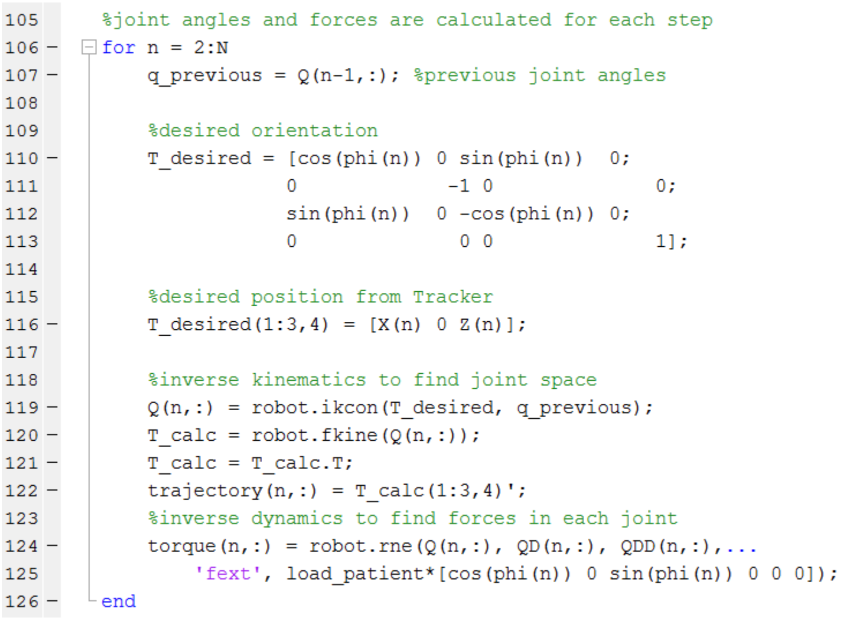


Figure 5.17: Illustration force orientation during forward bending.

$$\vec{F}(\phi) = [cos(\phi) \quad 0 \quad sin(\phi)] \tag{5.1}$$

Kinematic and dynamic calculations in Matlab

Appendix G includes the full script for calculating the path of the end effector and the resulting forces during forward bending. The next section is included to give further explanation of the most essential part of the script line 105-126 (Figure 5.18).



```
105       %joint angles and forces are calculated for each step
106 -   for n = 2:N
107 -         q_previous = Q(n-1,:); %previous joint angles
108
109           %desired orientation
110 -         T_desired = [cos(phi(n))  0 sin(phi(n))   0;
111                        0             -1 0            0;
112                        sin(phi(n))   0 -cos(phi(n)) 0;
113                        0              0 0            1];
114
115           %desired position from Tracker
116 -         T_desired(1:3,4) = [X(n) 0 Z(n)];
117
118           %inverse kinematics to find joint space
119 -         Q(n,:) = robot.ikcon(T_desired, q_previous);
120 -         T_calc = robot.fkine(Q(n,:));
121 -         T_calc = T_calc.T;
122 -         trajectory(n,:) = T_calc(1:3,4)';
123           %inverse dynamics to find forces in each joint
124 -         torque(n,:) = robot.rne(Q(n,:), QD(n,:), QDD(n,:),...
125               'fext', load_patient*[cos(phi(n)) 0 sin(phi(n)) 0 0 0]);
126 -     end
```

Figure 5.18: Excerpt from Matlab script for calculating kinematics and dynamics of forward bending.

Line 105-116: The loop starts at the second step because the initial position is already calculated. A [4x4] matrix is created with the desired orientation and position of the end effector (T-desired). The orientation is described as a rotation matrix [3x3] around the y-axis, that depends on the angle ϕ during the motion. As explained in section 5.1.3, ϕ is a linear interpolation from $0°$ to the required $75°$. The desired position vector of the end effector is set to the data point obtained with Tracker [X(n) 0 Z(n)].

Line 119: Inverse kinematics (robot.ikcon) are used to calculate the joint angles [1x7] to obtain the desired pose of the end effector (T-desired [4x4]. The previous angle of the joint space (q-previous [1x7]) is included in the function to be used as the start point for the numerical solution of the joint space. This reduces computational time and ensure smooth motion.

Line 120-122: Forward kinematics (robot.fkine) is used to calculate the position of the end effector based on the joint angles. This is used to plot the desired trajectory versus the calculated trajectory to ensure that the robot follows the desired path.

Line 124: Inverse dynamics (robot.rne) is used to calculate the torque in each joint [1x7] based on the external load in the end effector [1x6]. The input of the function is the angular position [1x7], velocity [1x7], and acceleration [1x7]. The velocity and acceleration are reduced to 0 (explained in Section 5.1.4). The external load is a six-dimensional vector of $[F_x \quad F_y \quad F_z \quad M_x \quad M_y \quad M_z]$. The load is changed during the motion (Figure 5.17).

5.1.4 Evaluation

Table 5.4: Motion platform - evaluation of product requirements. The feasibility score ranks from 0-3, where 0 is not feasible and 1-3 is low to high feasibility.

Requirement	**Assessed**	**Feasibility**	**Note**
Functional requirement	—	—	—
Motion/training space	Yes	2	Almost, see section below
Accuracy	Yes	2	Accuracy of 0.1mm. Accuracy of angle is confidential and unknown
Diagnostic through neutral motion	Yes	2	Tested in Munich, looked promising
6 Degrees of freedom	Yes	3	7 DoF
Establishment of training programs	Yes	2	Have not been tested, but should be possible from the specifications of the robot
Virtual walls	Yes	3	Yes. This is possible with the right configurations
Force control	No		
Load capacity	Yes	3	Simulations in Matlab did not exceed limitations
Smooth motion	Yes	3	Tested in Munich, should not be a problem
Assisting software	No	2	Not researched, but should not be a problem
Database for each patient	No	2	Not researched, but should not be a problem
Reachability	Yes	2	Almost, Section below
Weight	Yes	3	18 kg
Hygienic	No	2	Not researched but assumed yes
Safety requirements	—	—	—
Emergency button	Yes	3	Yes, already installed
Automatic stop	No		Unknown
Certified for intended purpose	Yes	2	Uncertain, Section below

Table 5.5: Motion platform - evaluation of user requirement. The feasibility score ranks from 0-3, where 0 is not feasible and 1-3 is low to high feasibility.

Requirement	Assessed	Feasibility	Note
Usage requirements			
Good user interface	No	3	Should be possible with right development
Sturdy and comfortable motion	Yes	3	Assessed in Munich
Design requirements			
Soothing color	Yes	3	Assessed in Munich
Non intimidating	Yes	3	Assessed in Munich
Hygenic	Yes	3	Assessed in Munich
Feel of quality	Yes	3	Assessed in Munich

Comments

During the trip to Munich, the requirements that were easy to test physically were assessed. Such as smooth motion, weight, hygienic, color, and design. Also, questions regarding the degree of freedom, virtual walls and emergency button, were answered during this trip (Table 5.5 and 5.4). Never the less, some of the parameters were not possible to test. This included force control, software interface, motion space and load capacity. Because of the author's knowledge and the time frame of the project, the load capacity and motion space were chosen to be assessed in this project. Therefore, control theory and software interface have to be assessed by students with a background from cybernetics and/or computer engineering.

Motion/training space

Forward/backward, sideways and rotational movement were tested with an initial position at $(0.419 \quad 0 \quad 0.370)$. The simulations concluded that the robot could manage all these paths, with the exclusion of the backward bending. When executing backward bending the robotic arm is retracted to the extent that it collides with itself (Figure 5.19).

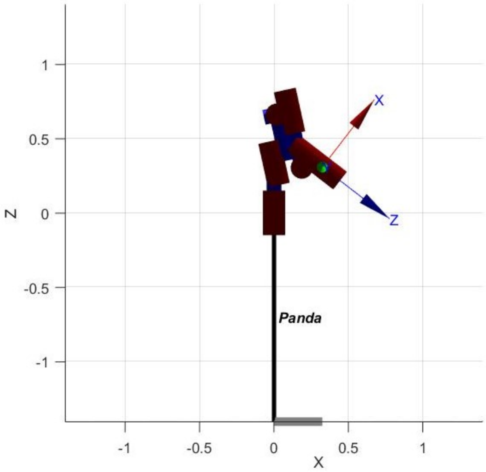


Figure 5.19: Plot of robot arm colliding in itself when performing backward bending.

The robot is not able to perform full backward motion when the base of the robot is placed in the current position. Figure 5.20 shows the desired trajectory from Tracker along with the calculated one from Matlab. When the robot reaches approximately x = 0.32, the motion is impossible, and the robot has to choose another path, not executing the full backward bending.

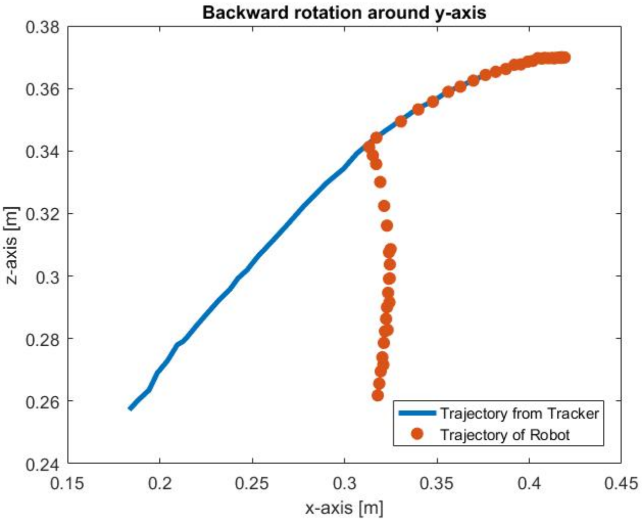
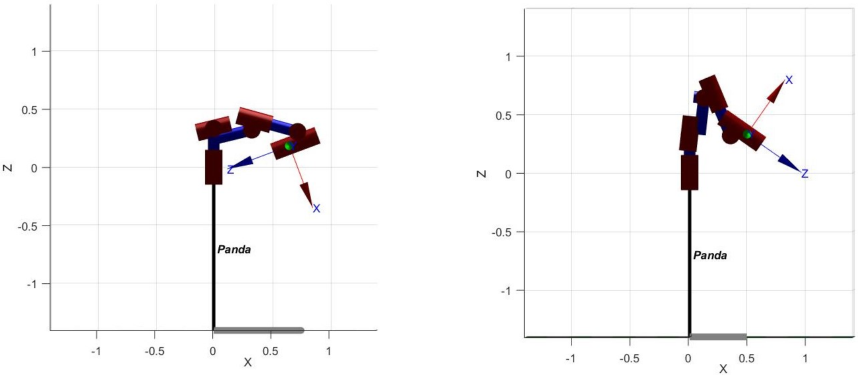


Figure 5.20: Trajectory from Tracker compared to the computed trajectory in Matlab when performing backward bending.

When performing forward motion, the TCP is translated approximately $250\,\mathrm{mm}$ along the x-axis and rotating $75°$ around the y-axis (Figure 5.21a). For backward motion, the translation is also approximately $250\,\mathrm{mm}$ and rotation of $-55°$ (Figure 5.21b). The task space required is therefore a $500\,\mathrm{mm}$ difference along the x-axis and a change in orientation by $-55°$ to $75°$. This is not possible to obtain by todays starting position. Note that the simulation in Figure 5.21b is based on a start position of $(0.720 \quad 0 \quad 0.440)$ thus enabling the full backward roation.



(a)

(b)

Figure 5.21: Required end pose for forward bending. Start position: $(0.419 \quad 0 \quad 0.370)$ (a). Required end pose for backward bending. Start position: $(0.720 \quad 0 \quad 0.440)$ (b).

As seen in Figure 5.21a and 5.21b, the robot is extended all the way out and rotating the end joints almost to max when forward bending, and very contracted and rotated to almost maximum in the opposite direction for backward bending. These two poses are not possible to obtain for the end effector when the base of the robot is placed in the current position.

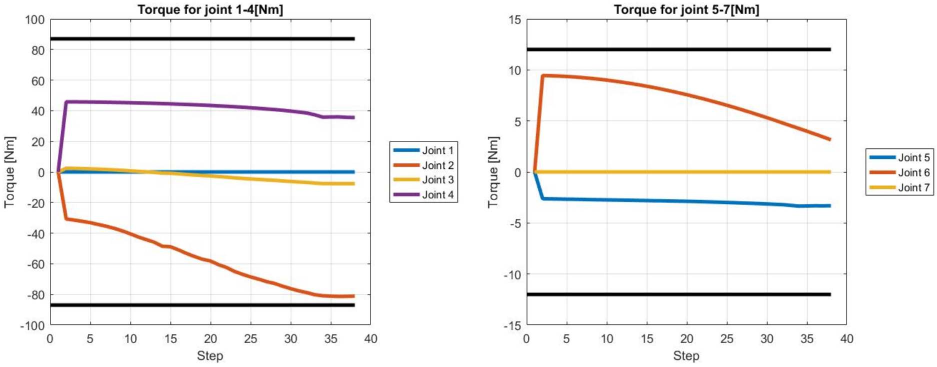
Hopefully this problem could be solved by placing the base of the robot or the patient in a different position. Future work should study this problem and try to find a suitable solution. If it is discovered that it is not possible to obtain the required training space in any configuration, a discussion will have to be made with FPMC to either reduce the training space or acquire a bigger robot. A bigger robot might result in a higher price and a more intimidating apparatus. Therefore, a compromise between training space, cost and size might be unavoidable.

Load capacity

Panda is a relatively small robot with a low load capacity. The maximum load of the first four joints is $87\,\mathrm{N\,m}$, and the final three are $12\,\mathrm{N\,m}$ (Appendix A). It was questioned if the robot could comprehend the loads associated with the training. The torque in each joint was computed for each motion path, to validate that it did not exceed the limitations. Note that it is no human risk related to the robot not being able to deliver high enough resistance. In the worst case, the robot will deliver a lower resistance than preferred, but there are no associated dangers for the patient.

This was verified with the method explained in section 5.1.3, physical test, video analysis and dynamic analysis in Matlab. For each motion path, the torques in each joint were generated during the motion and plotted. The plots were then inspected to ensure that all values stayed within limits. The sideways motions exhibited no problems and were well within limits (Appendix B). The rotational motion of $10\,\mathrm{N\,m}$ was mainly absorbed by the final joint, which can deliver $12\,\mathrm{N\,m}$ and is also within the limit (Appendix B).

The heaviest load of the robot is the forward bending. In this position the robot is extended to the maximum, creating a long torque arm onto joint 2. Luckily the torque in joint 2 stayed just beneath $87\,\mathrm{N\,m}$ (Figure 5.22a). Joint 6 was also near the limit, but stayed with in its limit of $12\,\mathrm{N\,m}$. Note that torques are probably higher than compared to a real-life test. The computer model is exaggerated regarding weight and the concentrated load of $40\,\mathrm{N}$ is almost the maximum force conducted by a healthy person. Plots of torques during every motion are found in Appendix B.



(a) **(b)**

Figure 5.22: Torque in joints conducted by forward bending. Joint 1-4 (a). Joint 5-7 (b).

Static model

The angular velocity and acceleration of the joints during the motion were reduced to zero. This means that the calculated torques are based on a static case, in each of the positions the robot moves through during the motion. This simplification was done because of the time frame and no adequate tools available for measuring velocity and acceleration. The simplification could result in a lower estimation of the torques, compared to a real case. However, the movement and acceleration are very slow, so the reduction to zero is not too far away from the real case. Besides, the model of the robot and the loads are exaggerated resulting in bigger forces. The conclusion that the robot can handle the related loads should still be valid.

Medical devices in medicine

By the definition of the Norwegian legislation regarding certification of medical devices from Section 2.3, the development of an apparatus for rehabilitation of whiplash patients will be subject to regulations. However, since the apparatus will be used purely in a physiotherapy manner, and will not be used in surgery or serve as an implant, the regulations are less severe. In addition, the finished product will need to be CE marked before it may be commercialized and sold on the European market. This marking proves that the product has been assessed and meets EU safety, health and environmental protection [51].

5.1.5 Summary

Section 5.1 proves that Panda fulfills most of the requirements for the motion platform. A lot of the requirements were demonstrated through a visit to Munich and technical specifications of the robot. The motion space and load capacity have been simulated in Matlab and concluded that the robot is strong enough, but unfortunately not able to deliver the required training space. This could be solved by placing the base of the robot in a different position (Section 6.2). The requirements not obtained in this project, are concerning control theory and software development of a user interface. The latter are important for the concept and needs to be studied further. In addition to these requirements, certification of medical equipment is crucial.

5.2 Head mount

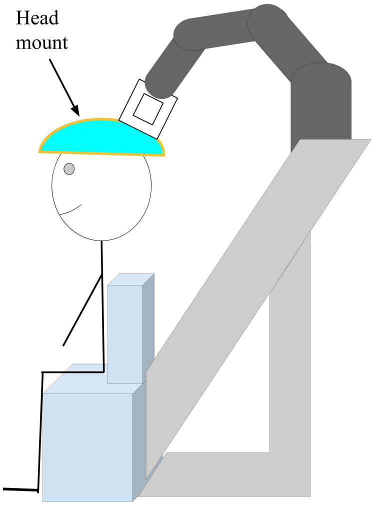


Figure 5.23: Head mount component of current concept

The head mount (Figure 5.23) is the part of the apparatus that will fix the patient's head to the mounting mechanism and the rest of the robot. Through this section, a total of four feasible designs has been assessed. The design involves a surrounding helmet with inflatable material inside to create a universal fixture coping with different head shapes. The best design is inflated by a manual bulb pump and has grooves for the patient's ears. A better design might be attained by a combination of the four feasible designs.

5.2.1 Requirements

Product requirement specification

Table 5.6: Head mount - product requirement specification.

Requirement	**Specification**	**Crucial**	**Beneficial**
Functional requirements	—	—	—
Universal fitting	Be able to fit any head shape and form	X	
Inflatable element(s)		X	
Manual inflation	Hand pump		X
Automatic inflation	Automatic pump with barometer		X
Symmetrical fixture	Forcing the head in the center of the head mount	X	
Quick procedure	Procedure of inflation should go fast		X
Do not obstruct neck movement	The head mount should not cover any part of the neck, because this would result in restrictive motions.	X	
Lightweight	Do not exceed 5 kg	X	
Chinstrap			X
Easy chinstrap fastener mechanism			X
Adjustable chinstrap			X
Replaceable inflatable elements			X
Ventilation system	Cooling		X
Production requirements	—	—	—
Easy to manufacture			X
Easy to modify design		X	
Interchangable parts			X

User requirement specification

Table 5.7: Head mount - user requirement specification.

Requirement	**Specification**	**Crucial**	**Beneficial**
Usage requirements	—	—	—
Easy to inflate	Problem free inflation	X	
User friendly	Self explaining way of fastening head		X
No slack or wiggling	None/minimal amount of looseness when inflated	X	
Comfortable	Inflatable pillows of comfortable material. Does not feel heavy		X
Easy operation of ventilation system	Reduce warmth when training		X
Easy to deflate		X	
Quick release	To get out of head mount in case of panic ect.	X	
Design requirements	—	—	—
Soothing color			X
Symmetric shape			X
Non frightening appearance	Do not induce stress	X	
Durable inflation pillows	Long lifetime		X
Hygienic	Easy to clean	X	

5.2.2 Method

The head mount was developed purely by the combination of building prototypes (Section 3.2) and iterative development (Section 3.1.5). Each specific concept was designed, built, tested and evaluated. Evaluations were based on comparing solutions with requirements from Table 5.12 and 5.13. Some components involving the helmet was developed through rapid prototyping using CAD and 3D printing and has not been further assessed. The main focus has been towards the form-fitting system with inflatables and their performance and comfort while testing them.

5.2.3 Concept

Previous work found that using inflatables along with a rigid outer shell were the most promising solution (Subsection 4.2.2). This is because the solution generates a uniform pressure on the patients head, and simultaneously supports a wide array of head shapes. However, further improvements can still be made. The specialization project of Brattgjerd concluded the use of an Etto helmet in combination with an inflatable pillow. The initial prototype was good, but improvements were needed.

Helmet: Further improvements for the helmet includes a chin strap for increased stability and Velcro strips to easily attach the pillows inside the helmet (Figure 5.24a).
Inflatables: Optimization and customization of inflatables to increase stability and comfort (Figure 5.24b).

(a)

(b)

Figure 5.24: Etto Twister (a) and inflatable neck pillow(b) (Appendix H.

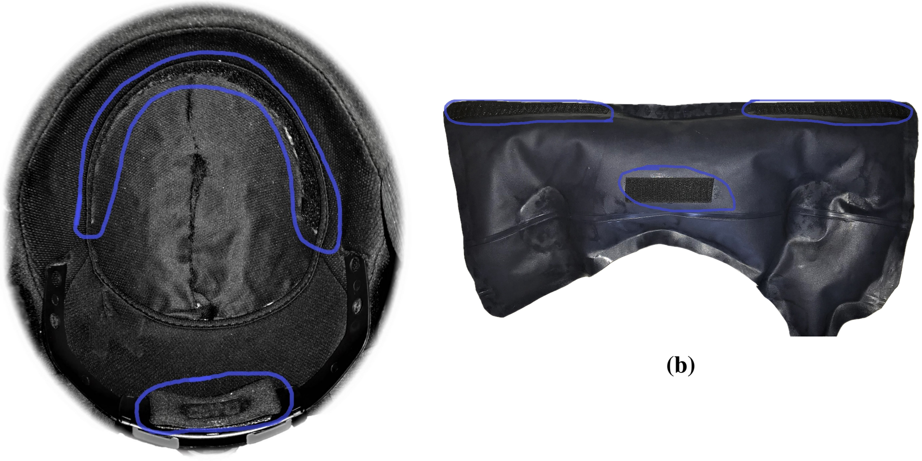
5.2.4 Development

Helmet

Figure 5.25: Head mount concept consisting of: mounting shim (1a), stop valve (1b), chin strap (1c), bulb pump and customized inflatable.

Small modifications were made to the helmet (Figure 5.25). The first modification was to move the fixing point of the mounting mechanism (Section 4.2.3), from the back to the top of the helmet. This was due to findings obtained in Section 5.1. A new mounting shim was designed through CAD and then 3D printed (Figure 5.25 1a). It creates a flat fixing surface necessary for the mounting mechanism. In addition, a chin strap was designed to increase stability (1c), by adding a fixing point at the patient's chin. The chinstrap was 3D printed and fitted with a 5 mm cushion of polyfoam for greater comfort.

The inflatable pillows are filled with air using a bulb pump, which also acts as a one-way valve. As a secondary precaution, a stop valve (1b) is included, thus preventing air from seeping out the tube. To fasten the different inflatables, Velcro strips are used. The strips are placed inside the helmet at appropriate places, to secure each particular pillow (Figure 5.26 and 5.27).



(a)

(b)

Figure 5.26: Placement of Velcro strips inside helmet (a) and on inflatable (b).

Figure 5.27: Head mount with inflatable pillow

Inflatables

Initially, a sheet of bubble wrap was placed inside the helmet as an approximation of the inflatables size and form. The bubbles would pop or gradually deform on places where the helmet pushed too hard towards the skull. The bubble wraps shape after the test was used as a base for designing the inflatables. Research on ”Do it yourself air pillows” uncovered the possibilities of making air pillows from garbage bags. Pictures from the prototyping can be found in Appendix C.

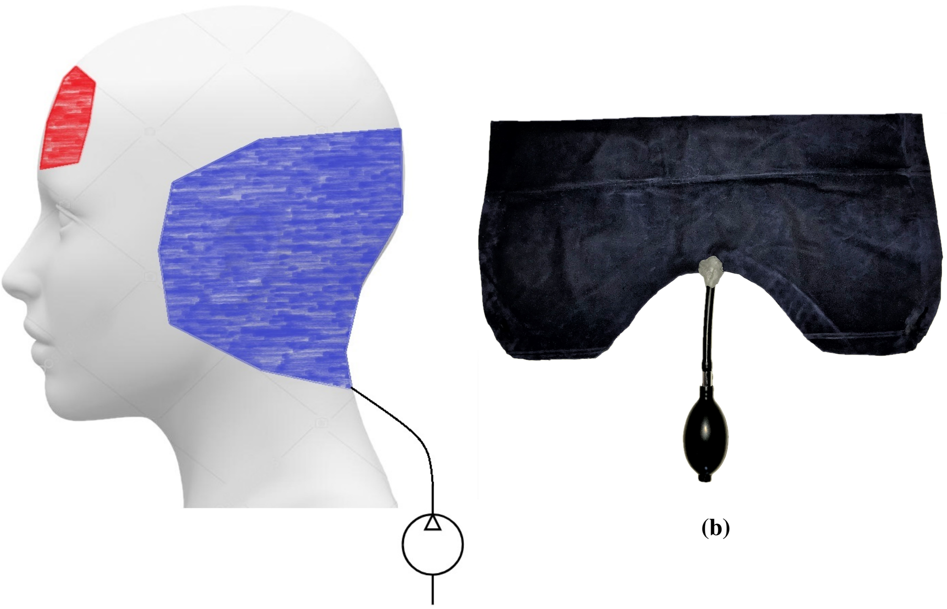
The prototypes were first made with bags of low-density polyethylene. Polyethylene melts without bursting when heated to 100° C. The melted areas creates an airtight seal, allowing the pillow to be designed in any shape. Melting the plastic was achieved through the use of a standard household iron. In addition, baking paper was placed between the plastic and the heat source, thus avoiding damage to the iron. The pillows were then tested through manual inflation by the bulb pump fitted with Blu-Tack. The most promising designs were produced in a more durable, $0.7\,\mathrm{mm}$ thick polyvinyl chloride (PVC) taken from an inflatable mattress.

To test each of the PVC inflatables, the same test set-up used in Section 5.1.3 was used. Motions were stopped the second the head mount started to succumb, and force/torque values were noted. Because of the low accuracy of the test set-up, the results were read with a certainty of $0.5\,\mathrm{kg}$.

The PVC pillows is considered a closed isochoric (constant volume) system since an approximation of no expansion of the PVC material was made. This is due to the relatively small difference in pressure from outside and inside the system (maximum 0.4 bar). After inflation, the patient’s body temperature will rise air temperature inside the system, and pressure will rise, according to the ideal gas law. The rise in pressure must also be taken into account when testing the inflatables, to ensure that the plastic welds will stay intact.

The following figures illustrates the corresponding pressure zones generated on the patients head. Pressure from the pillows are shown in the color blue, and pressure from foam pads inside the helmet are shown in red. A performance table follows each design with info regarding maximum forces and torque before the fixture started to give in.

Design 1: Single and large inflatable element



(b)

(a)

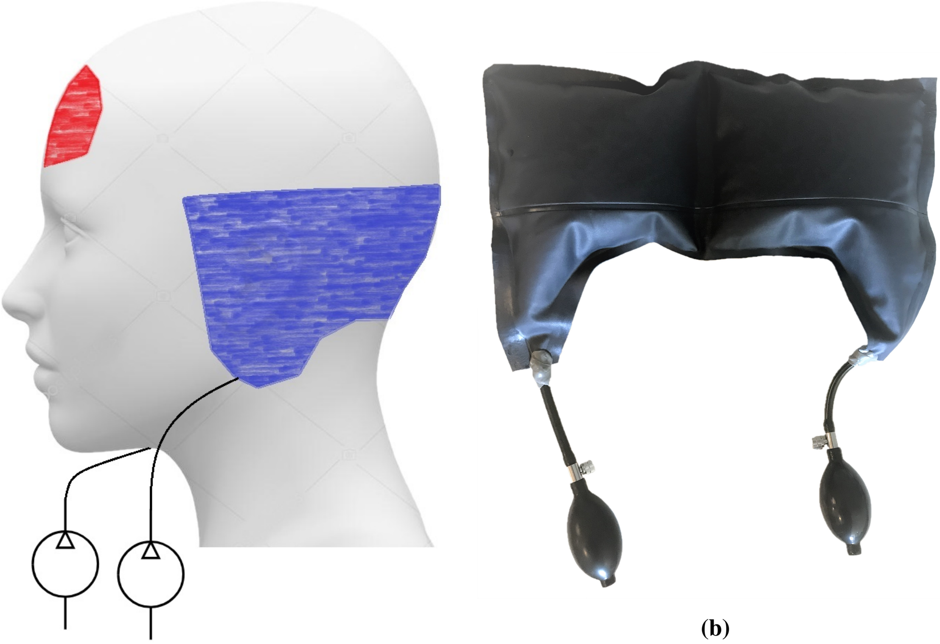
Figure 5.28: Design 1: Pressure zones against head (a) and the single large inflatable element (b).

Table 5.8: Fixing performance of the single and large inflatable element

Motion	**Force**[N]	**Torque**[N m]
Forward	40	-
Backward	35	-
Sideways	45	-
Rotation	-	10

The first design resembles a neck pillow (Figure 5.28), produced in PVC material covered with a thin layer of velour. Its shape covers the entire back of the head, including the patient's ears (shown in blue). Upon inflation, the patient's forehead is pushed towards the top part of the helmet (shown in red). The maximal volume of the pillow is 2.1 liters, measured by the displacement of fluids when immersing the fully inflated element in water (Appendix C).

Design 2: Inflatable element with two air pockets



(b)

(a)

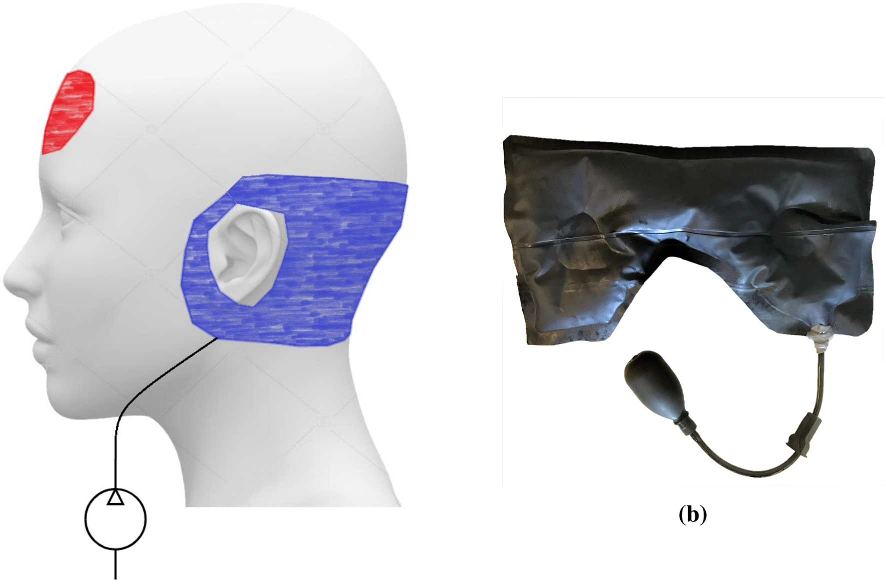
Figure 5.29: Design 2: Pressure zones against head (a) and the inflatable element with two air pockets (b).

Table 5.9: Fixing performance of the inflatable element with two air pockets

Motion	**Force**[N]	**Torque**[N m]
Forwards	40	-
backward	35	-
Sideways	45	-
Rotation	-	10

The inflatable element with two air pockets (Figure 5.29) should prevent air from moving from one side of the element to the other. It resembles the preceding element, except that its welded shut over the middle. The idea is to constrain the head even more when doing sideways motions. As a result, it requires one bulb pump on each side of the helmet. With regards to the total volume, it is the biggest element. When fully inflated it measures 2.4 liters.

Design 3: Inflatable element with ear slot



(a)

(b)

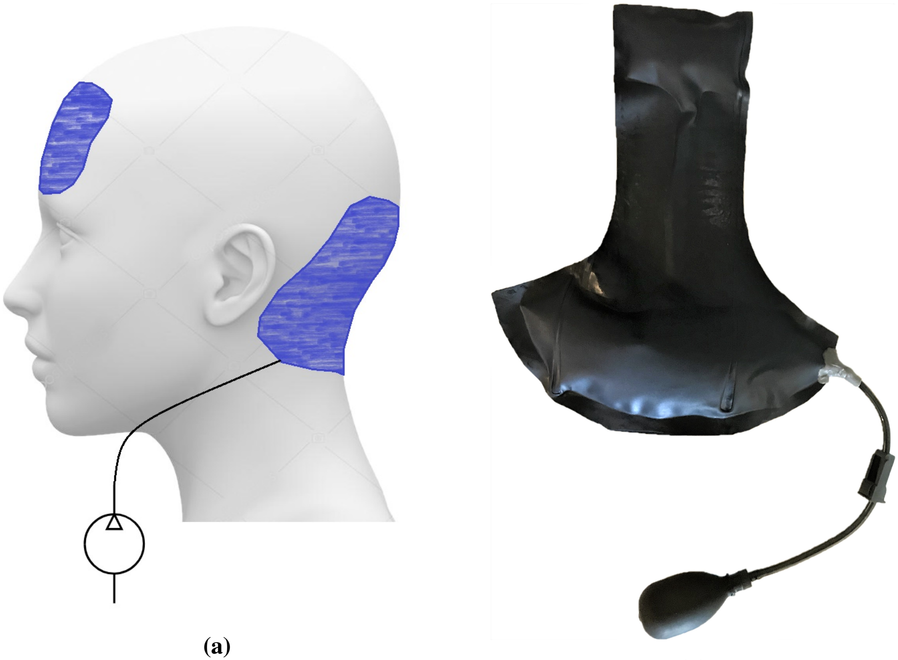
Figure 5.30: Design 3: Pressure zones against head (a) and the inflatable element with ear slots (b).

Table 5.10: Fixing performance of the inflatable element with ear slot

Motion	**Force**[N]	**Torque**[N m]
Forwards	40	-
backward	30	-
Sideways	40	-
Rotation	-	8

The inflatable element with slots for the patient's ears (Figure 5.30) is reduced down to a volume 1.5 liters when fully inflated. In correlation with the previous pillow, the tube connected to the pump is installed on the patients left side for easy accessibility. It also has an increased bulb pump size for faster inflation. By melting grooves for the patient's ears, comfort is improved. Also, this versions fixing capabilities was almost as good as the two prior designs (Table 5.10).

Design 4: Inflatable element with forehead air pillow



(a)

(b)

Figure 5.31: Design 4: Pressure zones against head (a) and the inflatable element with forehead pillow (b).

Table 5.11: Fixing performance of the inflatable element with forehead pillow

Motion	**Force**[N]	**Torque**[N m]
Forwards	60	-
backward	55	-
Sideways	15	-
Rotation	-	3

To test the efficiency of applying an even force onto the patient's forehead, an inflatable element with a forehead pillow (Figure 5.31) was made. The pressure is evenly distributed throughout the element by a small passage in the middle, shown in Figure 5.31b. This solution provides the smallest element, with a maximal volume of 1 liter. Due to its restricted shape and not having inflatable material on the area around the patient's temple, the solution had poor capabilities in rotation and sideways motion (Table 5.11). In forward and backward motions it performs better than its predecessors.

5.2.5 Evaluation

During the development, four different designs evolved. As a result, the following tables (5.12 and 5.13) account for the requirements resolved by all the inflatable elements. Following the tables comes an individual evaluation of each design.

Table 5.12: Head mount - evaluation of product requirements. The feasibility score ranks from 0-3, where 0 is not feasible and 1-3 is low to high feasibility.

Requirement	**Assessed**	**Feasibility**	**Note**
Functional requirements	—	—	—
Universal fitting	Yes	2	Section below
Inflatable element(s)	Yes	3	
Manual inflation	Yes	3	
Automatic inflation	No	2	Should be possible
Symmetrical fixture	Yes	3	
Quick procedure	Yes	3	With a big bulb pump
Do not obstruct movement	Yes	2	With the right design
Lightweight	Yes	3	Approximately 600g
Chinstrap	Yes	2	
Easy chinstrap fastener mechanism	Yes	3	
Adjustable chinstrap	Yes	3	
Replaceable inflatable elements	Yes	2	
Quick replacement of elements	Yes	2	
Production requirements	—	—	—
Easy to manufacture	Yes	2	
Easy to modify design	Yes	2	
Interchangable parts	Yes	2	

Table 5.13: Head mount - evaluation of user requirements. The feasibility score ranks from 0-3, where 0 is not feasible and 1-3 is low to high feasibility.

Requirement	**Assessed**	**Feasibility**	**Note**
Usage requirements	—	—	—
Easy to inflate	Yes	3	Yes when using a proper bulb pump
User friendly	Yes	3	
No slack or wiggling	Yes	2	Section below
Comfortable	Yes	2	Section below
Integrated fan	Yes	2	Section below
Easy to deflate	Yes	3	
Quick release	No		
Design requirements	—	—	—
Soothing color	No		
Symmetric shape	Yes	3	
Non frightening looking	No		
Durable infaltion pillows	No	2	
Hygenic	Yes	3	

Design 1: Single and large inflatable element

Advantages: The first impressions on the single and large inflatable element were good. The material, which consisted of PVC covered with a thin layer of cotton fabric was very comfortable. It also made a very sturdy fixture when appropriately inflated. The performance was also very good and close to the Pandas maximum strength.
Disadvantages: On the downside, the bulb pumps placement in the center at the back is very inaccessible, and it also takes a long time to inflate the element. After about 20 consecutive pushes, a decent pressure was established, but this will vary depending on different head sizes. During manufacturing, it was a problem making the material melt together, most likely caused by the cotton fabric. It was also noted that when making backward motions, the inflatable would interfere with the patient's neck, and obstruct movement. As a final remark, it was noted some ear fatigue after around 10 minutes of wearing the head mount.

Design 2: Inflatable element with two air pockets

Advantages: Having one pump on each side was a significant improvement concerning accessibility. The time of inflation was also cut in half due to the use of two pumps.
Disadvantages: The hypothesis about air moving from one side of the element to the other and causing slack when training, turned out to be wrong. There was no notable difference between using two pockets as opposed to one, which is also consistent when comparing the performance Tables 5.8 and 5.9. Using two separate air pockets resulted in more problems getting the same amount of pressure on each side. The size was also approximately the same as the first version and restricted backward motions. Worst of all was the material, which after just 2-3 minutes became very hot and caused both sweat and ear fatigue.

Design 3: Inflatable element with ear slot

Advantages: Making an opening for the ear turned out to be a great success with regards to hearing, comfort, and heat reduction. There was no ear fatigue detected after 20 minutes of use. Also, by using a bigger bulb pump, the process of inflation was done with just five consecutive squeezes. The overall size was also reduced, and backward motions could be made without any problems, and with almost the same performance.
Disadvantages: The design did not perform as good when doing sideways and rotational motion due to a lesser amount of material around the patient's temple. It was also a more difficult procedure of fitting the inflatable inside the helmet and getting the ear slots in the right position. Although the reduced size helped, the material would still cause heat and sweat after just a couple of minutes.

Design 4: Inflatable element with forehead pillow

Advantages: This design also avoids inflation over the ears and was perceived as very comfortable. It is also the smallest design, and inflation was done in seconds. Having an inflatable pushing towards the forehead resulted in the best performing design in forward and backward motions.
Disadvantages: Since the design does not cover the patient's temple region, the design

becomes very loose when doing sideways and rotational motions. The thin passage going to the forehead pillow also gets partly cut off when the helmet is worn. This resulted in longer inflation time.

5.2.6 Summary

Quickly generating prototypes of plastic bags during the initial stages, provided useful information on the optimal shape and size of the head mount. Through the evaluation of the four produced designs, the prototypes are close to fulfilling all the crucial requirements. The use of inflatables combined with the Etto Twister will, with an optimal inflatable pillow fulfill the crucial requirements of being comfortable, sturdy and have a universality as required, thus acquiring an optimal recovery training for patients with all head types. The largest bulb pump also made the designs easy to inflate and deflate, and an automatic inflation system seems excessive.

Considering the findings through the development process, it is desirable to make an inflatable element that combines design 3 and 4. The comfort by avoiding pressure over the patient's ear, and the firmness created by an inflation pillow that covers both the forehead, back of head and temple of the patient, will most likely be a success. There should also be experimented with different types of material that may be easier to work with and which also reduces unpleasantness related to heat. A ventilation system could be implemented by installing small internal fans, as seen inside more advanced motorcycle helmets.

For a more accurate way of testing, a better test rig should have been built. The use of a baggage weight and a moment wrench is very simple, and getting a stable repetitive result is hard. The use of a static digital torque wrench and an accurate load cell would improve the accuracy and repeatability of the results. As a last remark, the most promising head mount must be tested quantitatively on a more significant test set of different head shapes.

5.3 Chair

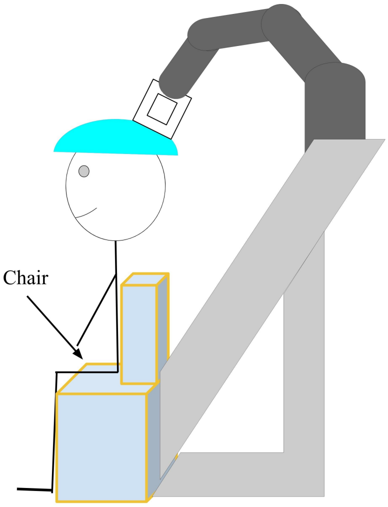


Figure 5.32: Chair component of current concept.

A chair (Figure 5.32) consists of an assembly of different components and most commonly serves to seat a single person. The chair used in this project is developed through modifying an existing office chair called Kinnarps 6000 through reverse engineering. It has been fitted with an electrical actuator and a rail system for stability and linear translation.

5.3.1 Requirements

Product requirement specification

Table 5.14: Chair - product requirement specification

Requirement	Specification	Crucial	Beneficial
Functional requirements	—	—	—
Height adjustment	Figure 5.33, a	X	
Backrest height adjustment	Figure 5.33, b	X	
Backrest angle adjustment	Figure 5.33, c		X
Armrest height adjustment	Figure 5.33, d	X	
Armrest width adjustment	Figure 5.33, e		X
Seat dept adjustment	Figure 5.33, f		X
Seat angle adjustment	Figure 5.33, g		X
Chair recline tilt	Figure 5.33, h		X
Lumbar support	Figure 5.33, i		X
Footrest			X
Maximum weight $>130\,\mathrm{kg}$		X	
Production requirements	—	—	—
Easy to manufacture			X
Easy to assemble and disassemble			X
Interchangable parts			X

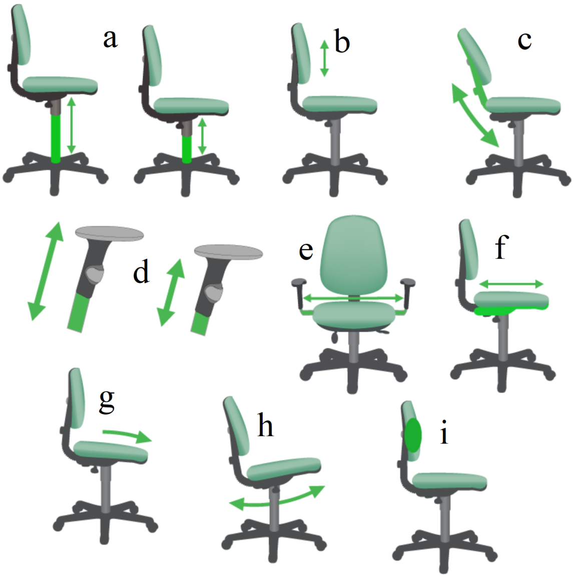


Figure 5.33: Chair functional requirements [52].

User requirement specification

Table 5.15: Chair - user requirement specification.

Requirement	Specification	Crucial	Beneficial
Usage requirements	—	—	—
Easy to adjust	Adjustable settings for each individual patient	X	
Establish a feel of quality			X
No slack or wiggling	Stable experience	X	
Comfortable			X
Fits everyone		X	
Easy to get in and out			X
Design requirements	—	—	—
Soothing color			X
Symmetric shape			X
Non frightening looking	Do not induce stress	X	
Durable	Long lifetime	X	
Hygenic	Easy to clean	X	

5.3.2 Method

The development of the chair was based on an already existing design. The requirement tables (5.14 and 5.15) served as guidelines when deciding which chair to acquire. After a chair was obtained, a top-down strategy, physical prototyping, and a design methodology called Set-based design was used.

The top-down approach is a way to gather and assess information and is widely used in product design. It involves breaking a product down into smaller parts and gaining meaningful insight into each specific component, also known as reverse engineering [53].

With regards to Set-based design (Section 3.1.4), useful functions of the existing chair is looked down, and parts, where the current chair design performs poorly or lacking, are developed further.

5.3.3 Concept

The initial intention was to develop an entirely new type of chair much like the deigns in the Kikreeide thesis [45]. However, with regards to the scope and timeframe of the thesis, a better way was to investigate current chair concepts and incorporate them into a design suitable for a rehabilitation apparatus.

5.3.4 Development

When investigating different chair models, there were a lot of promising candidates. The favorite models were a chair called Voldemar from IKEA [54] and the Steelcase Leap [55] office chair. They all possessed the necessary crucial requirements and ranged in price from 2200 to 6000 NOK. Since the purpose of this thesis was to make a proof of concept prototype, an investment of over 2000 NOK for a chair is undesirable.

After contacting the City hall of Levanger regarding used office chairs, the Kinnarps 6000 (Figure 5.34) was introduced. The office chair was offered for free and is currently retailing at 5000 NOK. Its dimensions are within the range of a broad array of human sizes, and it also has six different types of adjustments. It has adjustments for chair angle, chair height, width and height of armrests, seat depth and backrest height. The chair's height is adjusted by a spring loaded gas cylinder with a maximum travel of $125\,\mathrm{mm}$. The chair possesses 8 out of 10 crucial functions listed in Table 5.15 and 5.14, which leaves the elimination of slack/wiggling and reupholster to a material that is easier to clean and has a more suitable color.

Figure 5.34: Kinnarps 6000 office chair [56].

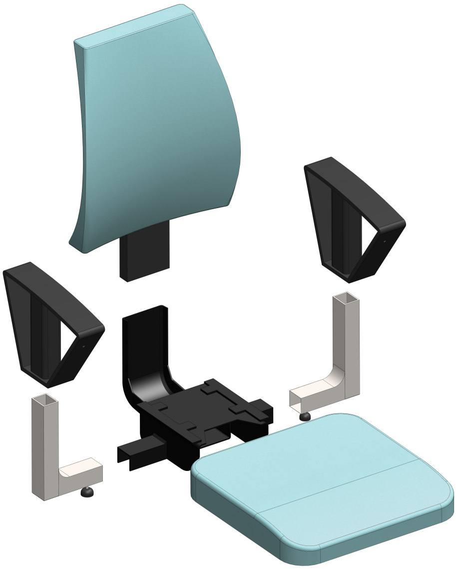


Figure 5.35: Locked functions of the original chair design.

Before development was initiated, specific functions and components of the original chair were locked and deemed as good enough for the final design. This involved the seat, backrest, and armrests. They were all joined together by the chair fixture plate underneath the seat (Figure 5.35).

The chair's mounting brackets for the gas cylinder, was far from as stable as required. Much wiggling was noticed, and when using persistent force on either of the sides of the chair, it would deflect almost 10-15 mm due to what seemed to be elastic deformation in the material. Another issue with the gas cylinder was the capability of only lowering the chair, and the patient would have to step off, for it to elevate.

Several solutions were generated in parallel by hand-drawn sketches and CAD models. Each design focused on resolving the weaknesses of the initial design. To prevent wiggling, a mechanism for removing rotations and translations in two plains was needed. The chair also needed to have the opportunity to raise an lower. Several plausible mechanisms were looked into, but an electrically controlled rail system became the most prominent.

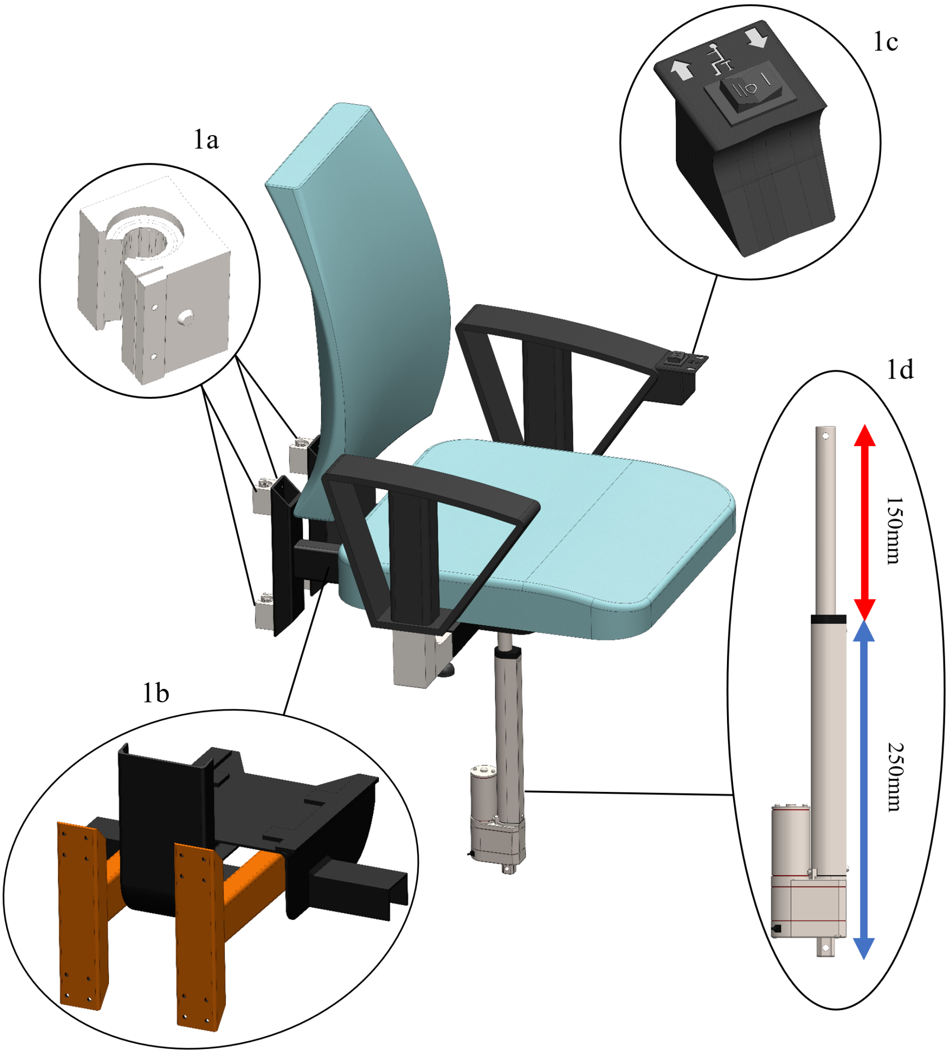


Figure 5.36: The modified Kinnarps 6000 with linear bearings (1a), four steel members welded to chair fixture plate (1b), DPDT switch (1c) and linear actuator (1d).

The solution uses an electrical actuator (Figure 5.36, 1d) that replaces the gas cylinder. The actuator allows the chair to be electrically elevated and lowered by a double pole double throw (DPDT) switch (1c). The four steel members (in orange, 1b), was welded together and fitted with four linear bearings (1a). The bearings slide on two parallel linear rails attached to the frame (revealed later in the chapter). This solution restrains the chair to only move in the desired linear translation (up and down) and removes unwanted looseness.

Figure 5.37 shows the bottom of the modified seat fixture plate. The left side has the linear bearings bolted to the welded steel members. An additional steel member was needed to cope with welding contraction during manufacturing. In the middle of the design is a customized bracket for attaching the electrical actuator. More pictures from the solution is shown in Appendix D.

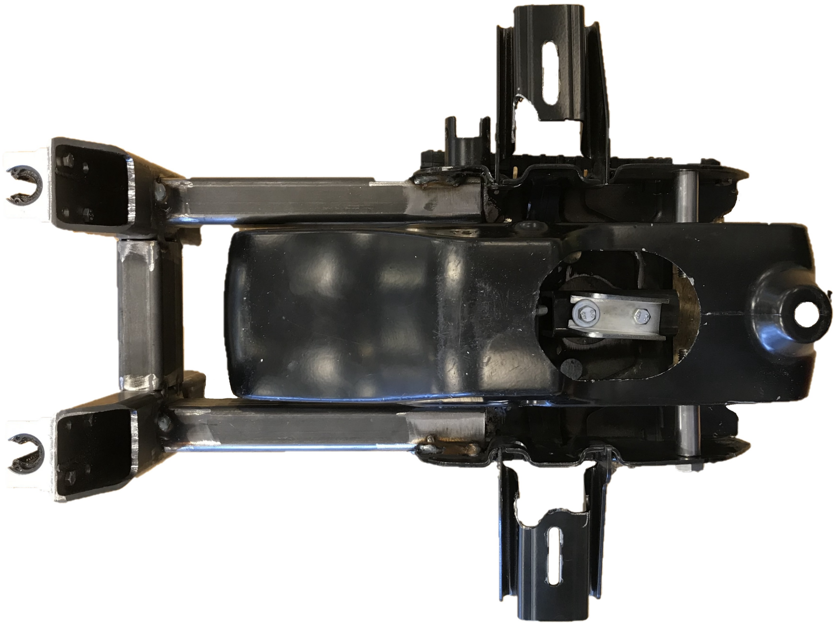


Figure 5.37: Modified Kinnarps chair fixture plate.

5.3.5 Evaluation

Table 5.16: Chair - evaluation of product requirements. The feasibility score ranks from 0-3, where 0 is not feasible and 1-3 is low to high feasibility.

Requirement	Assessed	Feasibility	Note
Functional requirements	—	—	—
Height adjustment	Yes	3	150 mm
Backrest height adjustment	Yes	3	5 levels
Backrest angle adjustment	Yes	1	15°
Armrest height adjustment	Yes	3	7 levels
Armrest width adjustment	Yes	3	80 mm difference
Seat dept adjustment	Yes	3	4 levels
Seat angle adjustment	Yes	0	None
Chair recline tilt	Yes	0	None
Lumbar support	Yes	0	None
Footrest	Yes	0	The height is adjusted so that the feet rests on the floor
Maximum weight $>$130 kg	Yes	3	150 kg
Production requirements	—	—	—
Easy to manufacture	Yes	0	Therefore an existing concept was obtained
Easy to assemble and disassemble	Yes	1	Requires some work
Interchangable parts	Yes	2	Possible to buy part

Table 5.17: Chair - evaluation of user requirements. The feasibility score ranks from 0-3, where 0 is not feasible and 1-3 is low to high feasibility.

Requirement	Assessed	Feasibility	Note
Usage requirements	—	—	—
Easy to adjust	Yes	3	
Establish a feel of quality	Yes	3	
No slack or wiggling	Yes	2	Some slack in backrest and armrest
Comfortable	Yes	2	Material might feel clammy
Fits everyone	Yes	2	Test with Lisa and Hugh
Easy to get in and out	Yes	3	
Design requirements	—	—	—
Soothing color	Yes	3	Light blue
Symmetric shape	Yes	3	
Non frightening looking	Yes	2	
Durable	Yes	2	
Hygenic	Yes	2	The faux leather is easy to clean of

Since the prototype used an existing chair, a lot of functional and user requirements were fulfilled, including adjustments to armrests, backrest, and seat (5.16 and 5.17). Some of the chairs functionality had to be reduced when attached to the frame structure. The ability to adjust the backrest angle was reduced, and seat recline tilt was removed entirely (Figure 5.33, c and h). The chair does not have lumbar support or footrest. A footrest was not crucial for the design, and is not needed, because the height is adjusted in a way that the patient can rest his or her feet on the ground.

The rest of the requirements were solved through modifications on the chair. The linear bearings reduce slack and wiggling when attached to the frame structure. The electrical actuator makes it possible to adjust the height without leaving the chair, which will be very beneficial for patients with reduced mobility. The armrests have some looseness when used, and should be revised.

The chair was given a new upholstery made with a light blue, faux leather. The upholstery gives the chair a soothing color and a non frightening look. In the final product, the faux leather should be replaced by real leather to avoid clamminess for the patient. A total of ten people have tested the chair, and the response to comfort and appearance were positive. However, an authentic impression is hard to obtain without the robotic arm in place.

5.3.6 Summary

This section has covered the development of the chair design. The design took base in an existing concept, which was modified to fit all requirements. The decision to chose an existing chair provided for free by Levanger municipality was made based on the available time and budget. A linear actuator was installed to give the chair automatic height adjustment and new upholstery to make the design less intimidating. The chair has been tested, and the response to comfort and appearance have been positive, thus indicating that the design is satisfactory. However, tests with different body types and reducing slack in armrests would be desirable.

5.4 Frame structure

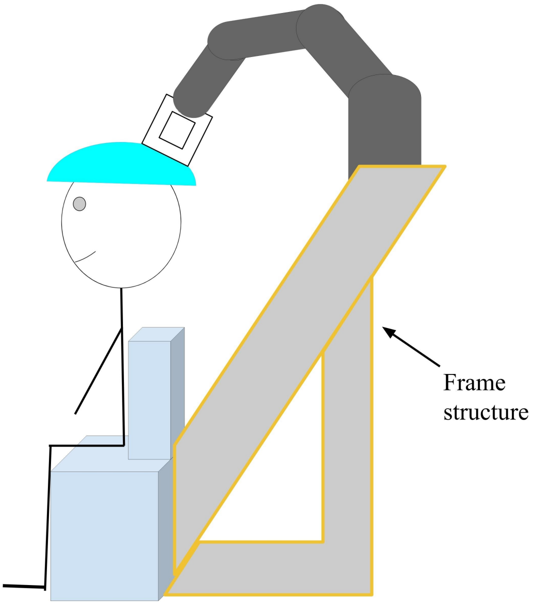


Figure 5.38: Frame structure component of current concept.

The frame structure (Figure 5.38) is a configuration of steel beams for incorporating the robot arm together with the chair. It consists of 120x80x5 members welded into a suitable design with a low center of mass for stability. It has drilled holes for fixing components, and one layer of silver paint giving it a pleasant look.

5.4.1 Requirements

Requirements for the frame structure were defined at the beginning of the project period to induce structure and to figure goals, obstacles, and limitations in the final design. The requirements were based on interviews with Morten Leirgul, requirements from the motion platform, and research on medical equipment.

Product requirement specification

Table 5.18: Frame structure - product requirement specification

Requirement	**Specification**	**Crucial**	**Beneficial**
Functional requirements	—	—	—
Stiffness	Displacement in base plate fixture should not exceed $2\,\mathrm{mm}$ in any direction	X	
Weight	Between 50 to $80\,\mathrm{kg}$		X
Adjustability	Can be adjusted to any patient body shape	X	
Standing or sitting option			X
Quick and easy mountable accessories			X
Production requirements	—	—	—
Easy to manufacture			X
Cheap material			X
Easy accesssible material			X
Easy to assemble			X
Interchangable parts			X
Environmental requirements	—	—	—
Recycable material			X
Low impact materials	Materials manufactured with low environmental impact		X
Non hazardous material			X
Easy and environmental friendly to dispose		X	

User requirement specification

Table 5.19: Frame structure - user requirement specification

Requirement	Specification	Crucial	Beneficial
Usage requirements	—	—	—
Easy to adjust	Easy to adjust settings for each individual patient	X	
Establish a feel of quality			X
No slack		X	
No sharp edges		X	
Safe to operate		X	
Design requirements	—	—	—
Soothing color			X
Symmetric shape			X
Blend into environment			X
Not frightening looking		X	
Quality appearance			X
Assembly requirements	—	—	—
Easy to assemble			X
Quick to assemble			X
Quick and easy mountable accessories			X
Self explanatory assembly and joining methods	Latch, screw, clasp	X	

5.4.2 Method

During the development process of the frame structure, two unique design methods have been explored and exploited, with focus on attaining requirements from Table 5.18 and 5.19. The first design is called *Hybrid design* and is developed through the Stage-gate model. The second design is called *Seated design* and emerged through iterative development. Later, the two methods would serve as an interesting side study upon the most optimal methodology to be utilized on the frame structure.

Stage-gate - Hybrid design

Hybrid design, has a composition of several solutions into one design, thus becoming more flexible and adjustable. The biggest difference between the two suggested designs is enabling the patient to do the rehabilitation training while standing upright. The development process was done by using Ulrich and Eppingers Stage-gate model, as disclosed in Section 3.1.2.

Iterative development - Seated design

Seated design was developed through iterative development from Section 3.1.5. Since it focused on the patients being seated, fewer components were needed for the solution. Each iteration underwent planning, designing, testing and reviewing. The testing was done through finite element analysis(FEA) and human modeling.

Human modeling

Based on the current concepts, the human modeling tool discussed in Section 3.3 can create human models that represent the desired percentile of the data population. This project uses two human models for evaluation. The models are named Lisa Smallings and Hugh Manning (Figure 5.39), previously introduced in Kirkeide's thesis [45]. Lisa represents the lower one percentile of the female body type, while Hugh represents the upper 99 percentiles of the male body type.

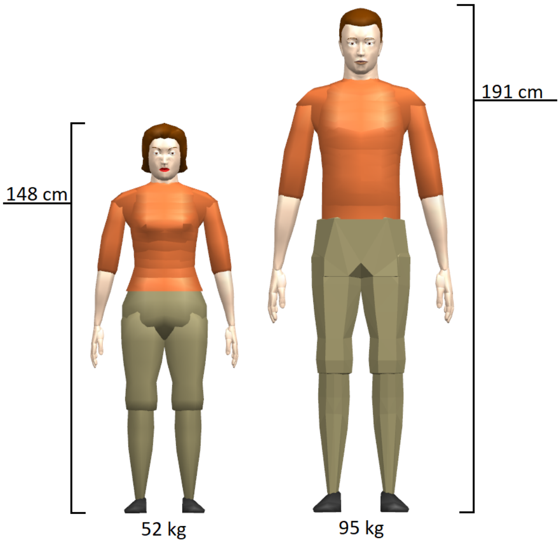
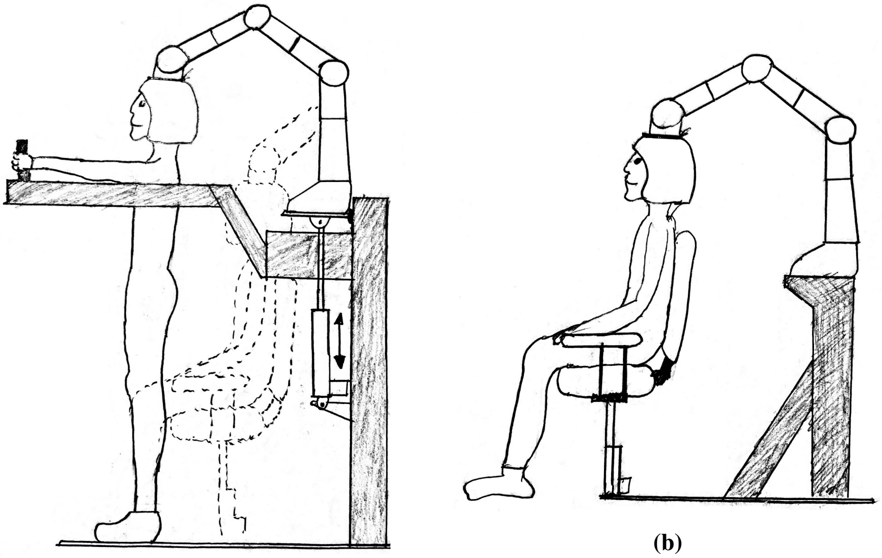


Figure 5.39: Lisa Smallings and Hugh Manning.

5.4.3 Concepts

The concept for the frame structure has been developed based on the designs made by Kirkeide, but with a new product development methodology approach. Hybrid design (Figure 5.40a) gives the patient the opportunity to conduct the rehabilitation training either seated or standing. The other design forces (Figure 5.40b) the patient to do the training while seated, hence the name Seated design.



(a)

(b)

Figure 5.40: Sketch of Hybrid design (a) and Seated design (b).

5.4.4 Development

Hybrid design

Development of Hybrid design was divided into the five first stages of the Stage-gate model. The last stage was not included since it concerns production ramp-up, which was not relevant for the project at its current stage. An initial plan was constructed focusing on the upcoming stages. Before the next stage was initiated, a broad range of design suggestions was sketched by hand, and only a few were feasible enough to pass the first gate and moving on to concept development.

Second stage focused on concept development and requirements. Based on both product- and user requirements, new solutions evolved through sketches. The most favorable solution proved superior and advanced through the gate. At the next stage (system-level design), more advanced sketches were developed, and critical components like linear actuators, control system, and linear rails with accompanying bearings were chosen.

Upon going through the next gate, the first design re-loop was unavoidable. This was due to the reason that the selected linear bearings were under-dimensioned, and would not support the applied force of a patient weighing more than 80 kg. Another, more durable and robust linear rail and bearing were chosen. At the detail design stage, the first CAD model of the design was generated. The materials were chosen along with appropriate joining methods of components. The CAD also exhibited precise dimensions of the frame structure and accessories needed for standing rehabilitation.

No problems were noticed when moving on to the last stage, called testing and refinement. By inserting the human models Lisa and Hugh, the proportions became apparent. Adjustments had to be done involving the total height of the frame and length of one of the linear actuators. This was due to problems regarding Hugh's possibility of doing standing rehabilitation. Modifications were done in the CAD and verified again in CAE and human modeling.

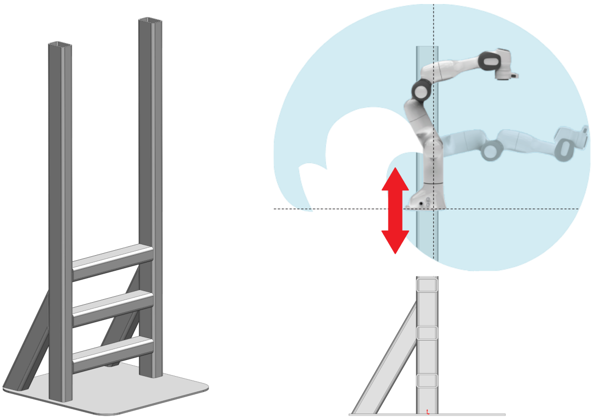


Figure 5.41: Hybrid frame structure.

The final solution offers a welded frame structure composed of 120x80x5 rectangular hollow sections (RHS) and a $10\,\mathrm{mm}$ steel plate with rounded edges (Figure 5.41). For the design to permit standing rehabilitation training, the robotic arm will need to be adjusted vertically to compensate for the patients height differences. It also needs to account for the different height between seated and standing rehabilitation. This is solved by using $12\,\mathrm{mm}$ linear rails and bearings (Figure 5.42, 1c), together with a 600-$1200\,\mathrm{mm}$ linear actuator (1b), and a custom made base fixture (1a). The bearings have a tolerance of $\pm 0.2\,\mathrm{mm}$, which will cause slack in the robots outer position of a maximum of $2.6\,\mathrm{mm}$.

When doing seated rehabilitation, the solution uses the modified office chair developed in Section 5.3. The actuator has a stroke of 250-$400\,\mathrm{mm}$ and should cover more than 99% of the western world's knee to heel length, according to the human modeling database in NX.

Figure 5.42: Assembly of Hybrid design, seated version, with the custom made base fixture (1a), linear actuators (1b, 1e), linear rails(1c) and chair fixture plate.

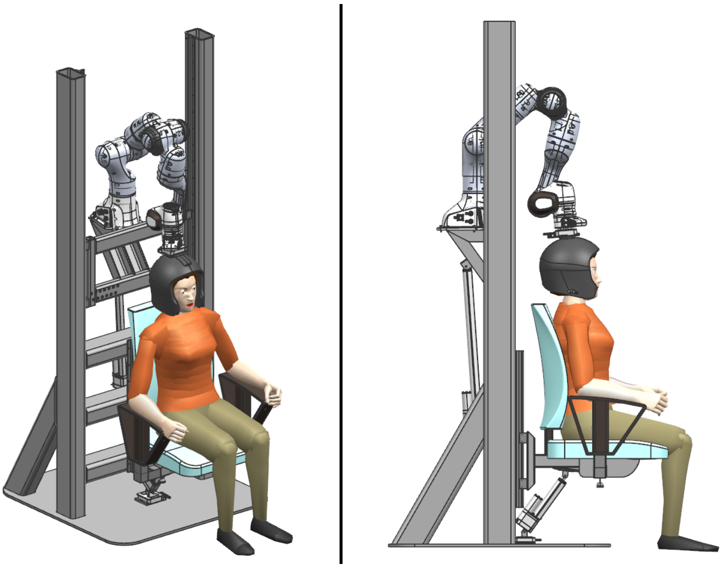


Figure 5.43: Lisa in seated position of Hybrid design.

Figure 5.43 and 5.44 shows how Lisa Smallings and Hugh Manning fits into the hybrid design using the seated position.

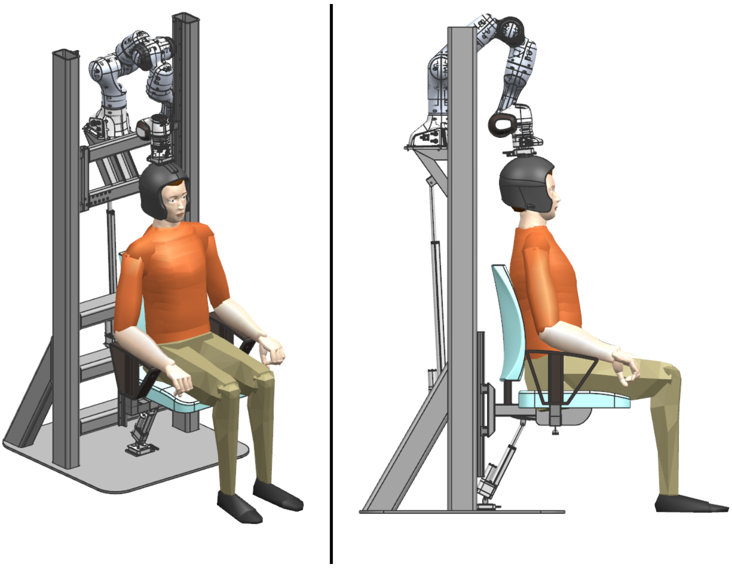


Figure 5.44: Hugh in seated position of Hybrid design.

The frame is designed in a way that should be intuitive and simple when changing from seated to standing position. The hitch pin is removed from the top actuator fixture (Figure 5.45, 2a), and the whole seat is lifted off the linear rails (2b, 2c). Cables for controlling the actuator are not shown but can be disconnected by using male/female spade connectors.

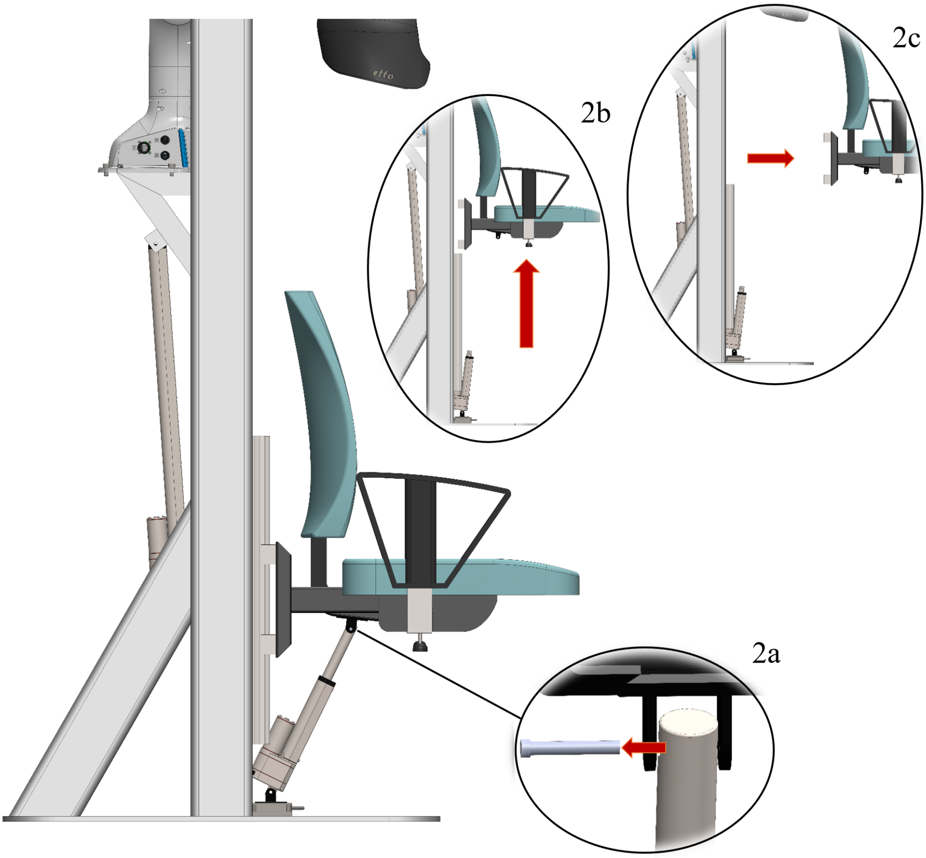


Figure 5.45: Seat removal by removing hitch pin (2a), and lifting chair off the linear rails (2b, 2c).

The standing position of the hybrid design requires some additional equipment in order to create a stable and secure fixture for the patient. When the seat is removed, an adjustable backrest (Figure 5.46, 3b) is mounted to the base fixture (3a). Additionally, two identical armrests with adjustable handles (3c), will secure the patient concerning horizontal movements and eliminate the use of a harness.

Figure 5.46: Assembly of Hybrid design, standing version, with custom made base fixture (3a), adjustable backrest (3b) and armrests (3c).

Each accessory is attached to the apparatus with milled slots on the custom made base fixture (Figure 5.46, 3a). Both the arm- and backrest have corresponding hooks that fit in the slots by doing a simple inward and downward movement. This design allows for a vast range of customization for the patients. The backrest has 12 different height levels with the help of a spring latch. The armrests have six levels to adjust for different shoulder widths, and finally, the handles can be adjusted for different arm lengths.

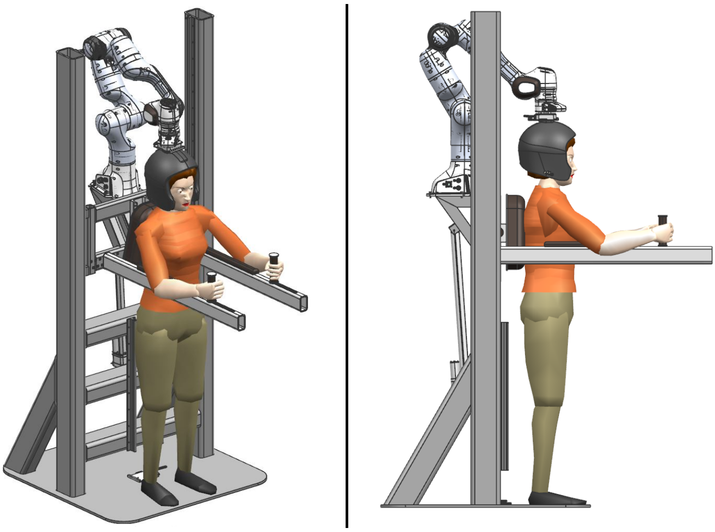


Figure 5.47: Lisa in standing position of Hybrid design.

Figure 5.47 and 5.48 shows how Lisa Smallings and Hugh Manning fits into the hybrid design when using the standing position.

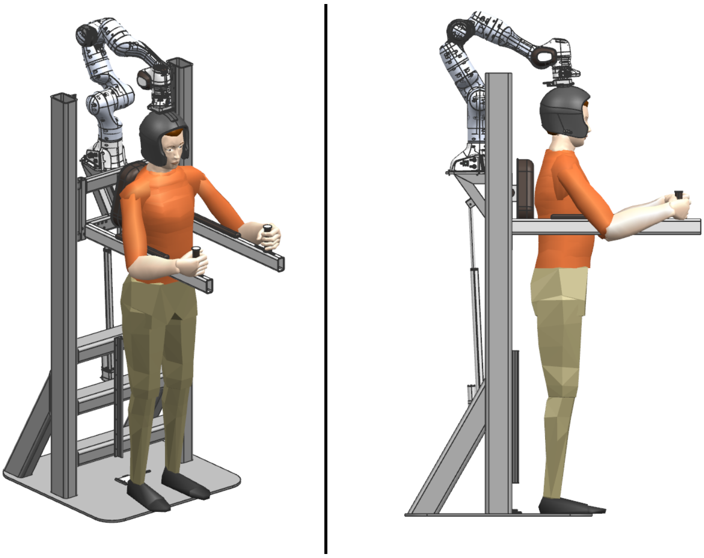


Figure 5.48: Hugh in standing position of Hybrid design.

Seated design

Seated design was developed using an iterative development approach (Section 3.1.5). Each design iteration had a focus on being flexible as discussed in Section 3.1.3, and went through four stages; planning, designing, testing and evaluating. An initial checklist was developed with a basis in the crucial product and user requirements in Section 5.4.1. Another checklist was created with a basis in the beneficial requirements. Each design iteration of the frame structure focused on checking off as many requirements as possible.

The first design iteration was very simple. The frame composed of a 10 mm base plate with a triangle shape and a fixture for the robot arm on top (Figure 5.49). Unfortunately, the design proved too unstable, and the fixture points on the base plate would easy deflect when adding horizontal forces. Second design iteration had a different appearance but exhibited the same problem as the first one. The third design iteration was better. This design could easily cope with the forces, but would easily tip backward when the patient was not seated in the chair due to instability and a high center of gravity.

The fourth iteration solved this with additional supports at the back of the structure. The stiffness was within limitations when considering displacements in the material during rehabilitation. The design did not make it all the way to manufacturing due to the difficulties of bending square tubes, and a new iteration was needed. The fifth design iteration only used material and manufacturing methods available in the workshop, but became significantly over-dimensioned and was consequently discarded.

The last three design iterations are relatively similar. They all have a large and heavy base structure for lowering the center of gravity. An angle on the beam going up to the fixture point of the robot provides room for the patient with regards to backward motions under rehabilitation. The final design has three parallel fixing points for linear rails, and drilled holes for electrical wires.

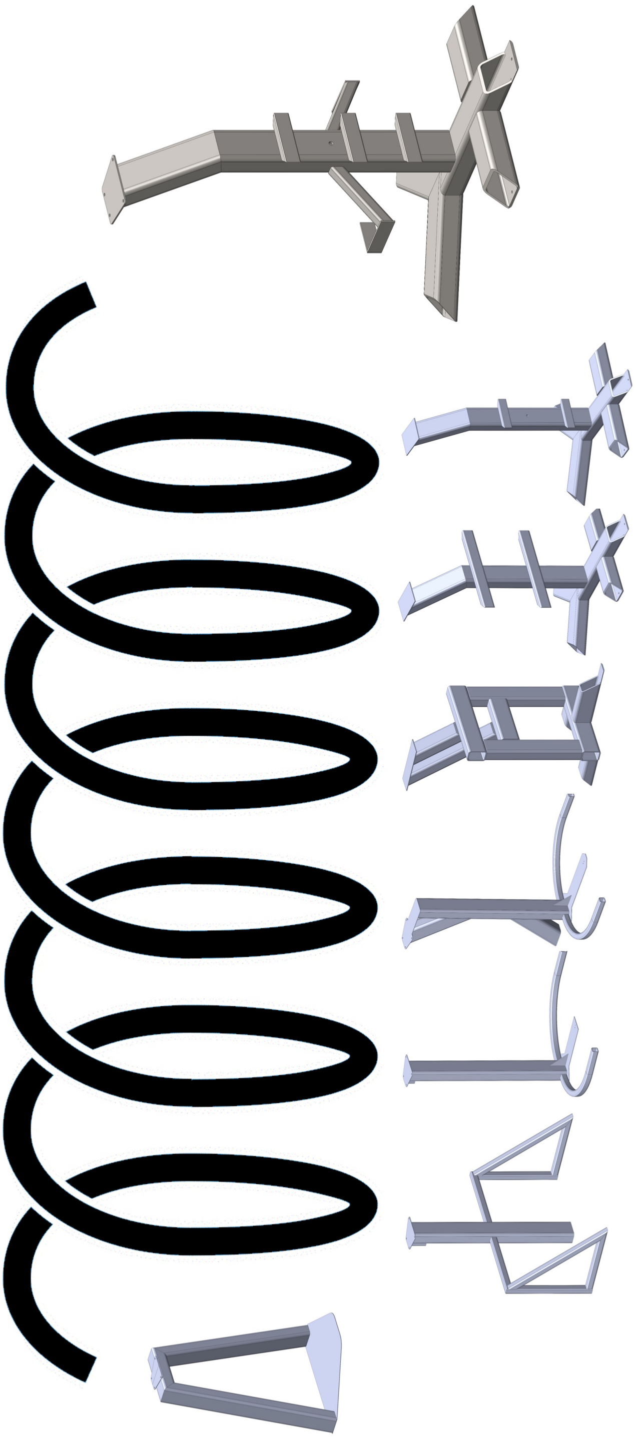


Figure 5.49: Eight iterations of Seated frame design.

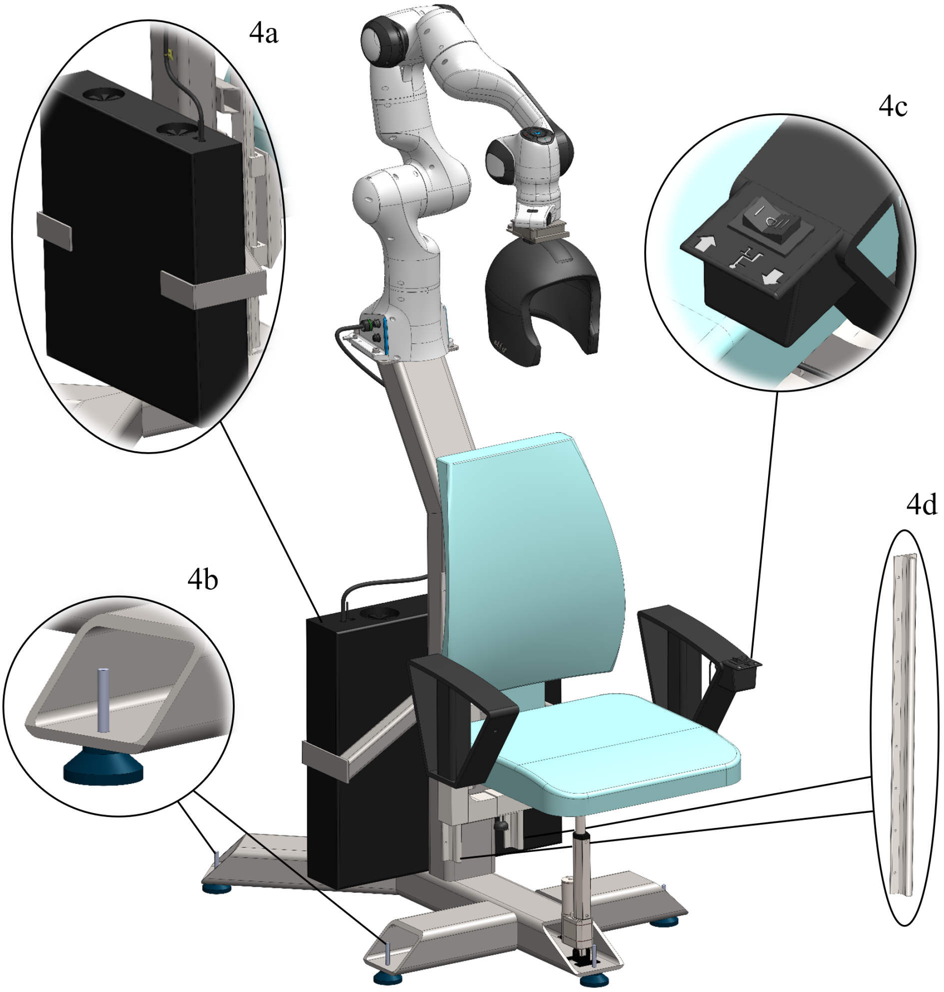


Figure 5.50: Seated design with attachment for control unit (4a), leveling feet (4b), DPDT switch (4c) and linear rails (4d).

Figure 5.50 shows an assembly of the final design iteration along with all the components. The Frame structure composed of seven welded beams of 120x80x5 profiles providing stability to the structure, and fixing points for the other components. The beams have a 45 degree cut on each end with regards to design and accessibility of wiring. Because of weld retraction and imperfections, leveling feet are installed on each beam-end (4b) to ensure that the frame is perfectly level, thus providing a leveled base for the robot arm. A finite element analysis gave a maximal displacement of $1.2\,\mathrm{mm}$ on the robots mounting plate when forces in the robot arm were set to 1.5 times the maximal strength.

Also, there are three 50x30x4 profiles used as fixing points between the main frame and the linear rails. The backside of the frame has an attachment for the robots control unit (4a). The design uses the same seat as developed in Section 5.3. Linear rails and a 250-400 mm electrical actuator provides height adjustments. The 12 mm linear rails (4d) are the same used in Hybrid design and provides increased stability for the chair. The actuator is controlled by a double pole, double throw (DPDT) rocker switch (4c) screwed to the left armrest of the seat.

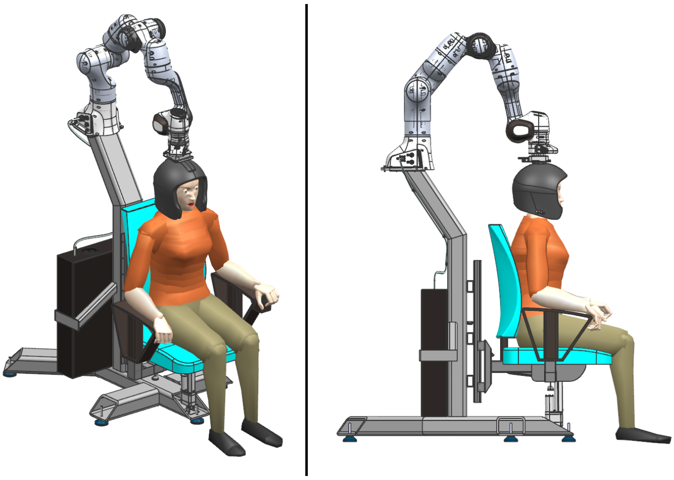


Figure 5.51: Lisa in Seated design.

Figure 5.51 and 5.52 shows how Lisa Smallings and Hugh Manning fits into the seated frame design.

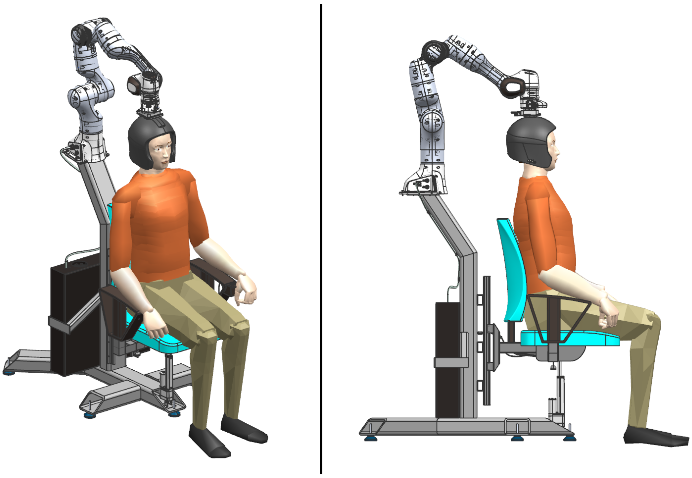


Figure 5.52: Hugh in Seated design.

Proof of concept prototype

After an assessment of Hybrid- and Seated design with regards to requirements, and available time and resources, Seated frame structure was chosen to be manufactured into a proof of principle prototype.

When realizing the prototype, the CAD-models were followed accurately. The RHS profiles were cut, drilled and welded together, and placements of the rails, chair, button, and actuator were mounted according to the model. This can be seen by comparing Figure 5.50 and 5.53. However, the top RHS member with the fixture plate for the robot was kept from the design as long as possible. This was an attempt to keep the frame structure flexible until enough information on the robots training space was acquired.

During prototyping, new problems were discovered, and some extra features and solutions had to be added. When adjusting the height of the chair, it was discovered that the electrical wiring from the actuator to the button needed the ability to extend and contract to cope with the height difference of the chair. This was solved by making the wire flexible by a process called *pig tailing*. Pig tailing was achieved by coiling the electrical cables surrounded by a heat shrink, around a small steel pipe of diameter $10\,\mathrm{mm}$. The cables were then heated above the glass transition temperature (GTT) of the heat shrink, proceeded by rapid cooling. This resulted in a coiled cable (Figure 5.53, 5a). Figure 5.53, 5b, shows the power-supply and 3A fuse for the actuator. The power-supply delivers 12V and 5A to the actuator.

In the prototype, a four-point harness was installed. During testing, the belts tended to fall over the sides of the backrest. This problem was solved by a 3D-printed belt clip glued with epoxy on the back of the backrest, thus keeping the belts in place (5c). Finally, the entire frame was spray painted with a silver aluminum coating. This gave the apparatus a more soothing color that fits well with the light blue color of the chair, making it less intimidating. The prototype ended up costing just under 2000 NOK (F), excluding prices for steel beams and welding wire.

Figure 5.53: Proof of concept prototype with pig tailed wire (5a), power supply (5b), seat belt clip (5c), and DPDT switch (5d).

5.4.5 Evaluation

Hybrid design and Seated design are evaluated individually. Seated design has a more thorough evaluation due to information gathered in the proof of concept prototype. The seated design also evaluation tables (Table 5.20 and 5.21) generated from assessing the development all the way from simple sketches to realization.

Hybrid design

Method
The method for developing the hybrid design turned out to be the most soothing with regards to work-load. The requirement tables were a great help when going through the planning stage, and establishing a reasonable time frame. However, having only two people evaluating the designs made passing through gates a bit too easy. Focus on progress became more relevant than doing re-evaluations and optimizations. More design-loops would probably have transpired if a stricter policy at the gates had been established, most likely transforming the final design noticeably.

Stability

The decision of using linear rails and bearings for the chair seemed like a perfect solution, especially after settling on the stronger $12\,\mathrm{mm}$ kit as a result of the design re-loop. Simple calculations looked promising for eliminating slack and wiggling. This could not be said when applying the same solution for raising and lowering the robotic arm on the custom made base fixture. By hand calculations and unconfirmed bearing tolerances given by a Chinese supplier, the total slack of $2.6\,\mathrm{mm}$ in the robots outer position is unreliable. Using the 600 - 1200 electrical actuator will also most likely create some form of instability. A solution may be to use more expensive and sophisticated square, computer numerical control (CNC) guide rails, and one or two high-quality linear actuator(s).

Using a slot and hook mechanism to fasten the additional equipment when standing also remains untested. The solution was adopted from a training apparatus at a fitness center and worked well for its purpose. The armrests could have been fitted with an additional bolt attachment to ensure its stability. However, implementing this solution will, most likely, result in longer fastening time.

Design
A soothing design was seen as the least important aspect of the apparatus as the focus has been on creating a proof of concept prototype. As of now, the apparatus looks fairly nice but may seem frightening to some patients. Components like the electrical actuators, linear rails and cables should not be exposed in the open for the patient to see. Making a boxed enclosure of plastic around the RHS profiles could have a good potential.

The usage of accessories to enable standing rehabilitation seemed like a good solution. The only problem is having loose parts stored away, and bringing them up when needed. Instead, the armrests should be foldable and fixed to the apparatus. Additionally, the custom-made base fixture is responsible for raising and lowering, both the robotic arm and the armrests simultaneously. The two actions should be done individually, since lowering the armrests results in lowering the robot and changing the motion space. This would also be required for adjusting the apparatus to patients with distinctive lengths between head and elbows.

Seated design

Table 5.20: Seated design - evaluation of product requirements

Requirement	**Assessed**	**Feasibility**	**Note**
Functional requirements			
Stiffness	Yes	3	
Weight	Yes	3	Approximately 60 kg
Adjustability	Yes	2	Section below
Standing or sitting option	Yes	0	Only possible in the hybrid design
Quick and easy mountable accessories	Yes	0	In the hybrid design
Production requirements			
Easy to manufacture	Yes	2	
Cheap material	Yes	3	
Easy accesssible material	Yes	3	
Easy to assemble	Yes	2	
Interchangable parts	Yes	2	
Environmental requirements			
Recycable material	Yes	1	
Low impact materials	Yes	2	S355 steel
Non hazardous material	Yes	2	Spray paint
Easy and environmental friendly to dispose	Yes	2	

Table 5.21: Seated design - evaluation of user requirements

Requirement	Assessed	Feasability	Note
Usage requirements			
Easy to adjust	Yes	3	
Establish a feel of quality	Yes	3	
No slack	Yes	2	
No sharp edges	Yes	2	All edges are angle grinded
Safe to operate	Yes	3	
Design requirements			
Soothing color	Yes	3	
Symmetric shape	Yes	3	
Blend into environment	Yes	2	
Not frightening looking	Yes	2	
Quality appearance	Yes	2	
Assembly requirements			
Easy to assemble	Yes	-	Applies only for hybrid design
Quick to assemble	Yes	-	Applies only for hybrid design
Quick and easy mountable accessories	Yes	-	Applies only for hybrid design
Self explanatory assembly and joining methods	Yes	2	Bolts, pins and rails

Method

The method for developing the seated design was very time-consuming. Every design iteration needed different types of accompanying components and accessories to make the solution applicable, which resulted in much time researching suppliers and design solutions. Ideally, the method should have been used in a much bigger team, and not by only two people. Although the final design became very good, the cost in time and work became almost three times the amount compared to the hybrid design.

Usually an iterative development approach needs a lot of front-loading. This was impossible to do in a group of two people. Only one design could be worked on at a time, while an optimal process would have designs running in parallel. This resulted in longer time applied to the initial development stages.

Product requirement overview

With respect to the product requirement table, all the requirements have been assessed and given a feasibility score. The stiffness with regards to the displacement of the fixture plate for the robot was within limits. The entire design is welded, and some details will consequently affect the frames adjustability. For maintenance or repairs, the chair can be removed in the same manner as shown in Figure 5.45. With regards to manufacturing and assembly, the frame structure is relatively easy to produce, but a bit time-consuming.

With regards to environmental requirements, the structure composes of welded steel beams weighing around 60 kg. The carbon print of producing such material in Norway using renewables are not bad. Hazardous material is mostly related to the spray paint added when coating the structure.

User requirement overview

Adjustability on the seated frame structure relates to the raising and lowering of the chair. This is done merely through the DPDT switch. The structure establishes a perfect feel of quality due to the linear rails for extra stability. Almost no slack is noticed when testing the proof of concept prototype. It is also very safe to operate and has no dangers related to pinching, instability and incorrect use.

With regards to design, the aluminum color should blend in with other apparatus or devices at the physiotherapists. It also has one plane of symmetry which is suiting. Intimidation and fear could not be adequately assessed without the robot arm and patients. The people that have tried the chair had little to say about the frame structures design. Some positive comments were made regarding the solution of hiding electrical wires inside the frame structure. The same could also be done for wires attached to the robot. For a more reliable assessment, the design must be evaluated by actual whiplash patients through visual and physical tests and rehabilitation including the Panda robot arm.

Prototyping

By building the seated design and creating a proof of concept prototype, even more, information could be gathered from the design. Initially, all the different tube lengths were cut, fitted with drilled holes and then welded. The process was relatively quick with regards to the design for manufacturing(DFM). Problems occurred during assembly, where some bolts were very hard to attach because of inaccessibility. More focus on design for assembly(DFA) in the CAD models would have helped.

Solutions that worked exceptionally well is the quick assembly and disassembly of the chair by removing the actuator hitch pin. However, the chair is still connected to the electrical wires, and installation of male/female spade connectors would free the chair entirely. The solution of pig-tailing the wire for flexibility also worked well.

During testing, the DC power supply did display some voltage drops when raising the electrical actuator with loads over 100 kg. This is expected, but the power supply is not CE marked, and with regards to safety, another, more reliable source of power should be invested. The DPDT switch is also a cheap, China manufactured component, and broke during testing because of residual voltage spikes in the system. This can be solved by installing a flyback diode in the circuit. The electrical actuator, on the other hand, is CE marked, and is rated for a maximum of 150 kg, and performed well.

5.4.6 Summary

During the development of the frame structure, two different designs have emerged. One design called Hybrid design is developed through the Stage-gate model. Another is called Seated design and is developed through iterative development. In the end, a proof of concept prototype was created based on Seated design.

Comparing the two development methods, shows that the Stage-gate model was a much better approach considering the size of the team. Additionally, Hybrid design only used one-third of the developing time compared to Seated design. The reason is that front-loading enough resources in iterative development is almost impossible for small teams. Iterations are produced very slow, and teams of at least three designers would have been preferred as iterations could be developed faster and in parallel.

Neither of the two designs are perfect, but with regards to time and resources available, the more straightforward Seated design was developed into a proof of concept prototype. During prototyping, new information was gained, and the final design was improved. To determine the full potential of the prototype, it has to be tested along with the Panda robot arm.

Chapter 6

Conclusion

6.1 Conclusion

Problem description

This assignment should focus on further development of an apparatus used for recovery training of whiplash patients. The development should advance as far as possible, and will preferably resolve into a proof of concept prototype. There are mainly four major components of the apparatus to be developed:

- *Investigate the robotic arm Panda, as the motion platform*
- *Head mount*
- *Seat for the patient*
- *Framing the structure of the apparatus*

Motion platform

The use of Panda as the motion platform was investigated using a computer model in Matlab. The training space and load capacity were simulated and tested to validate Panda as the motion platform. Simulations show that Panda is not able to deliver the training space when based in the current position. Panda can deliver forward, sideways and rotational motion, but not full backward motion. Further investigations are necessary to conclude if Panda can deliver the training space with other configurations of the prototype and base position. The torque load in each joint during the motion paths were simulated. The tests concluded that the torque load in each motor never exceeds its limits. If it is discovered that Panda is not able to deliver the training space in any configuration a discussion with a physiotherapist is necessary to conclude whether to use a bigger robot or reduce the training space. A compromise between training space, cost and size may be unavoidable.

Head mount

The head mount advanced to a working prototype (Section 3.2). The head mount uses an alpine helmet from Etto with customized inflatable inserts made of durable PVC material. The most prominent design of the inflatables has grooves for the patient's ears. Tests concluded that the head mount is both comfortable and able to deliver a good fixture under the related training forces. It was discovered that a design with additional inflatable material on the patient's forehead increased the stability even more, and should be considered to be included in the final design. In conclusion, a head mount consisting of inflatables and a rigid outer shell will serve as a very good fixture for the patient's head. The working prototype should be used for further testing and optimization to realize a functional prototype.

Chair

A working prototype of the chair was realized using a modified office chair called Kinnarps 6000. By utilizing reverse engineering and PD methods, the final design is fitted with a new upholstery, five steel members welded to the original structure and a linear actuator for height adjustment. The back of the chair is fitted with a rail system for stability and linear translation when using the actuator. Fellow students that tested the chair gave positive feedback, but a structured test with feedback from patients is required to advance to a functional prototype.

Frame structure

The frame structure was developed through iterative design and prototyping and resulted in a proof of concept prototype. The frame structure is designed and developed to incorporate all the components into a stable and soothing design. It consists of large 120x80x5 RHS beams welded together and leveling feet for a horizontal construction. It has a fixture plate for the robot, linear rails and attachment points for the chair. Electrical cables are hidden or fixed to the frame to increase the appeal of the design. The positioning of the robot needs to be solved to advance the proof of concept prototype, to a working prototype. Figure 6.1 shows a test of the proof of concept prototype.

Figure 6.1: Author sitting in the proof of concept prototype.

6.2 Future work

The project reached all the goals from the problem description by investigating the robot and advancing the apparatus to a proof of concept prototype with some components reaching the status as working prototypes. This chapter recommends next steps to improve the designs further.

Panda by Franka Emika

The current design does not allow the robot to perform full backward bending. It is crucial to find a base position that enables Panda to perform the full training space. Because of the short reaching length of only one meter, this could be difficult, and the robot might need to be placed in a non-traditional position. For example, positioning the robot above or right behind the patient could allow for a full motion space (Figure 6.2). The designs might result in a more intimidating apparatus, and feedback from patients is crucial to finding a good compromise. Hopefully would an easy solution placing the base of the robot at an angle (Figure 6.3), increase the training space and eliminate problems regarding the frame structure and perception of the apparatus. This will need to be assessed.

(a) **(b)**

Figure 6.2: Possible placements of the Panda robot upside down (a) or at 90° (b).

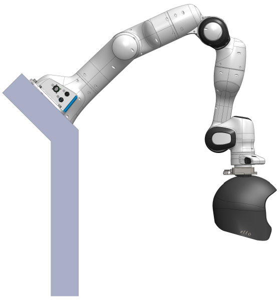


Figure 6.3: Panda with 45° angle of robot base.

The process of testing this with a computer model is complicated and requires much time. It is recommended to do the tests physically, either with Panda or by building a scaled-down model.

Head mount

As discussed in subsection 5.4.5 an inflatable element having grooves for the ears, and covers both the forehead, back of head and temple of the patient is recommended. A breathing material improving comfort should also be investigated. The design should subsequently be evaluated by testing several candidates with different head shapes.

Frame structure

The frame structure will be highly dependent on findings regarding the placement of the robot arm. If the base of the Panda can be placed at 90° or 45°, simple modifications to the existing prototype can be done. If the upside-down placement proves to be most beneficial a new frame structure will have to be made. As mentioned in Section 5.4.6, feedback from patients regarding the current appearance of the apparatus, is important before the next development stage.

6.3 Project evaluation

A detailed plan of the project was established in the beginning. The main limitations of the project were the available competence, time and money. The goal of the project was to make a proof of concept prototype of a head mount, frame structure, and seat along with making a final validation and decision of the robot arm.

It was decided to distribute the tasks, because of Brattgjerd's knowledge in CAD and Festøy's knowledge in Matlab. The idea, process, and design would be discussed together. Brattgjerd would make the CAD-models and lead the building of the prototypes, while Festøy would generate a computer model of the robot arm and assist Brattgjerd when needed. The distribution of tasks worked well. It allowed for individual work which increased flexibility for the authors. Underway, solutions were discussed, and from the different point of views, better solutions emerged. The different background was helpful in a way that the authors had different techniques for solving a problem. This resulted even more diverse and innovative solutions.

Brattgjerd had done previous research in his specialization project. He had visited Firda to interview Morten Leirgul, a physiotherapist with over 20 years in the business. A company visit to Franka Emika in Munich was also made, to observe the robot arm in real life. Based on interviews with Morten Leirgul user and functional requirements for each component were established. Based on the requirements and time frame, a detailed plan and suitable product development method were chosen for each component. Money was limited, and the goal was to realize the prototype as inexpensive as possible. The prototype was realized for under 2000NOK (Appendix F), not including steal and welding wire.

The plan concerning each component worked well and increased efficiency. In hindsight, an additional plan for the concept as a whole would be preferable, for example including what order the components should be developed, and how the design of the different components was constrained by each other. The lack of a project plan had some advantages and some disadvantages. Working on all the parts in parallel allowed for greater flexibility. Multiple components could be developed at the same time, but problems on one component could transpire, resulting in new design iterations, for already developed components.

The investigation of Panda should have been done before the frame structure because the entire frame is very dependent on the motion platform. The discovery of the limitation of the motion space was not discovered until the end of the project. This will result in a new design loop of the frame structure, where the robot needs to be placed in a different configuration. The design loop could have been avoided if the research on the robot arm had been done before the development of the frame. For this master's thesis, it would not have been possible to realize a proof of concept prototype after an investigation of Panda, due to the available time. For the next group of students, it is recommended that the needed placement of the robot arm is determined before further development on the frame.

The proof of concept prototype of the frame structure cannot be used for backward motions, but the value of the design iterations and the physical model needs to be underlined. Many issues and good solutions have been uncovered during the product development process, which will serve as an excellent base for the new students continuing the development. Stage-gate (used for Hybrid design) was more efficient and served more advantages than iterative (used for Seated design) when developing the frame structure. By using the different development methodologies, the Hybrid design is now less flexible than the Seated. In addition, the Seated design of the frame structure has many advantages concerning changing the position of the arm because of the information obtained through the iterative development process. The use of prototyping on the Seated design also enables the design to be tested by patients regarding comfort, appearance, and functionality:

- Comfort
  - Does it fit different body types?
  - Is it comfortable to use for a long time?
- Appearance
  - Is the color soothing?
  - Does it look intimidating?
- Functionality
  - Is the patient fixed?
  - Is there places where wiggling needs to be reduced?

In any product development process, feedback from the target group is crucial. Because of the time frame, only tests by fellow students and supervisor have been made. It is crucial to get feedback from patients with whiplash injuries that potentially will use the new apparatus.

It was interesting to test different product development methodologies and consequently see their advantages and disadvantages through a real-life example. It was noted that it is easier to use something that exists and modify it rather than to develop something from scratch. This accounts for the head mount, chair, and robot arm. It would result in a lot of unnecessarily time and effort to develop a chair or an alpine helmet from scratch. Unfortunately, a component may not always fulfill all the requirements, and modifications or/and compromises are sometimes unavoidable.

The multidisciplinary cooperation has been highly valued by the authors and resulted in a project with great breadth and accomplishments. It is interesting to gain knowledge in different technical fields and use different viewpoints to elevate design solutions to challenging problems.

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Appendix A

Technical data sheet

TECHNICAL DATA

Technical specifications

Panda research

TECHNICAL DATA [1, 2]

Arm	
degrees of freedom	7 DOF
payload	3 kg
sensitivity	joint torque sensors in all 7 axes
maximum reach	855 mm
joint position limits [°]	A1: -170/170, A2: -105/105, A3: -170/170, A4: -180/5, A5: -170/170, A6: -5/219, A7: -170/170
joint velocity limits [°/s]	A1: 150, A2: 150, A3: 150, A4: 150, A5: 180, A6: 180, A7: 180
Cartesian velocity limits	up to 2 m/s end effector speed
repeatability	+/- 0.1 mm (ISO 9283)
interfaces	▪ Ethernet (TCP/IP) for visual intuitive programming with Desk ▪ 1x input for external activation device ▪ Control connector ▪ Hand connector
interaction	buttons for: guiding, selection of guiding mode
mounting flange	DIN ISO 9409-1-A50
installation position	upright
weight	~ 18 kg
protection rating	IP30
ambient temperature	+15°C to 25°C (typical) +5°C to + 45°C (extended) [3]
air humidity	20% to 80% non-condensing
Control	
interfaces	▪ Ethernet (TCP/IP) for Internet /network connection ▪ power connector IEC 60320-C14 (V-Lock) ▪ Arm connector
controller size (19”)	355 x 483 x 89 mm (D x W x H)
supply voltage	100 V_{AC} - 240 V_{AC}
mains frequency	47- 63 Hz
power consumption	▪ max. 600 W ▪ average ~ 300 W
active power factor correction (PFC)	yes
weight	~ 7 kg
protection rating	IP20
ambient temperature and air humidity	see Arm
Pilot	
interaction and remote control	navigation pad and buttons for: Hand/Desk control mode, OK, SAVE, CANCEL

Hand	
parallel gripper	with exchangeable fingers
grasping force	force up to 70 N
travel (travel speed)	80 mm (30 mm/s)
Desk [4]	
platform	via browser on regular devices
architecture	distributed, service-oriented
programming	visual & intuitive, dialog-based
Apps	can be composed into complex workflows to create Tasks and Solutions
Panda research [5]	
Franka Control Interface (FCI)	General information ▪ Ethernet based communication up to 1 kHz [6] ▪ provided as C++ library Control modes ▪ gravity & friction compensated joint level torque command ▪ desired joint position or velocity command ▪ desired Cartesian position or velocity command ▪ Hand control Feedback data ▪ measured joint data ▪ low-level desired joint goals ▪ estimation of externally applied torques and wrenches ▪ various collision and contact information
Robot Model Library	▪ forward kinematics ▪ Jacobian matrix ▪ inertia, Coriolis and gravity terms
ROS support	▪ access to Franka Control Interface (FCI) from ROS ▪ URDF model of Panda research
license	non-commercial use only

[1] **technical data is subject to change**

[2] the user is responsible for the performance of a risk analysis and safe operation of the robot in accordance to its intended use and applicable standards and laws

[3] performance can be reduced when operating outside the typical temperature range

[4] Desk is deactivated when using the Franka Control Interface (FCI)

[5] view ANNEX for further information

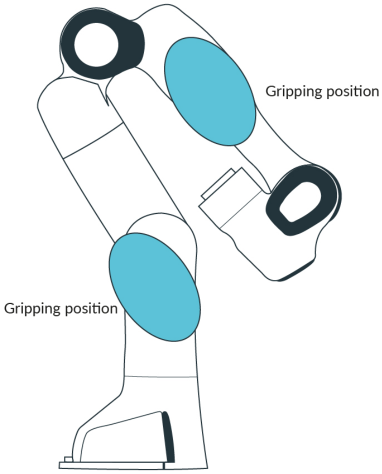
[6] depending on computing equipment and network setup

Additional technical operating conditions

Respect torque limits for each joint at all times:

- Axes 1 & 2: allowed, repeatable peak torque <= 87 Nm
- Axes 3 & 4: allowed, repeatable peak torque <= 87 Nm
- Axes 5, 6, 7: allowed, repeatable peak torque <= 12 Nm

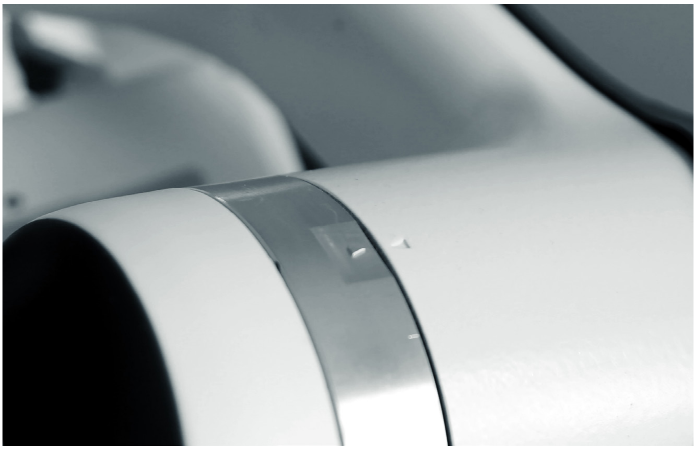
Transport position of Arm and indication of handling positions



- According to the joint angles of axis 1 to 7: [0°, -32.08°, 0°, -170.17°, 0°, 0°, 45°]
- The Arm may only be handled in the positions indicated here

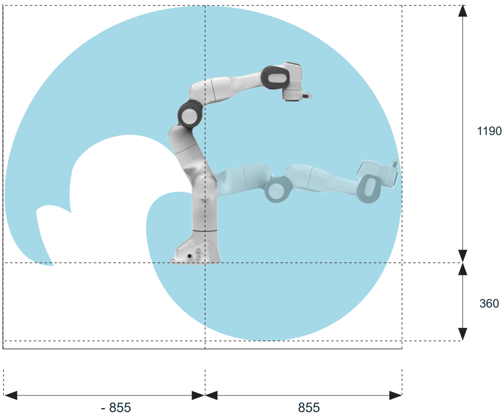
Zero position

The mechanical zero position of the joints is reached when the two triangles on each side of the gap between the Arm segments align.

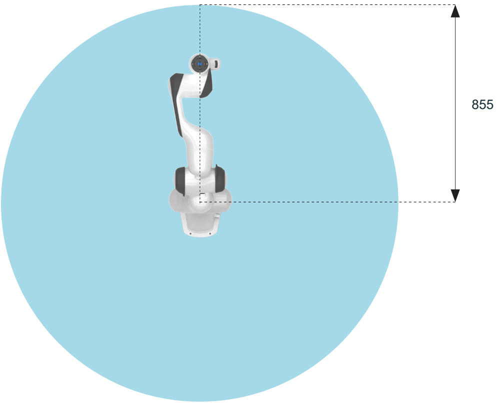


Operating space

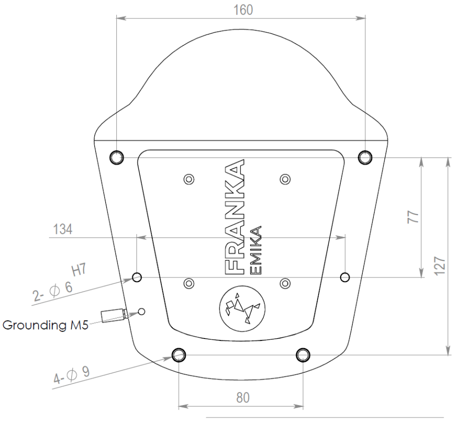
Side view of motion range:



View from above:



View from below

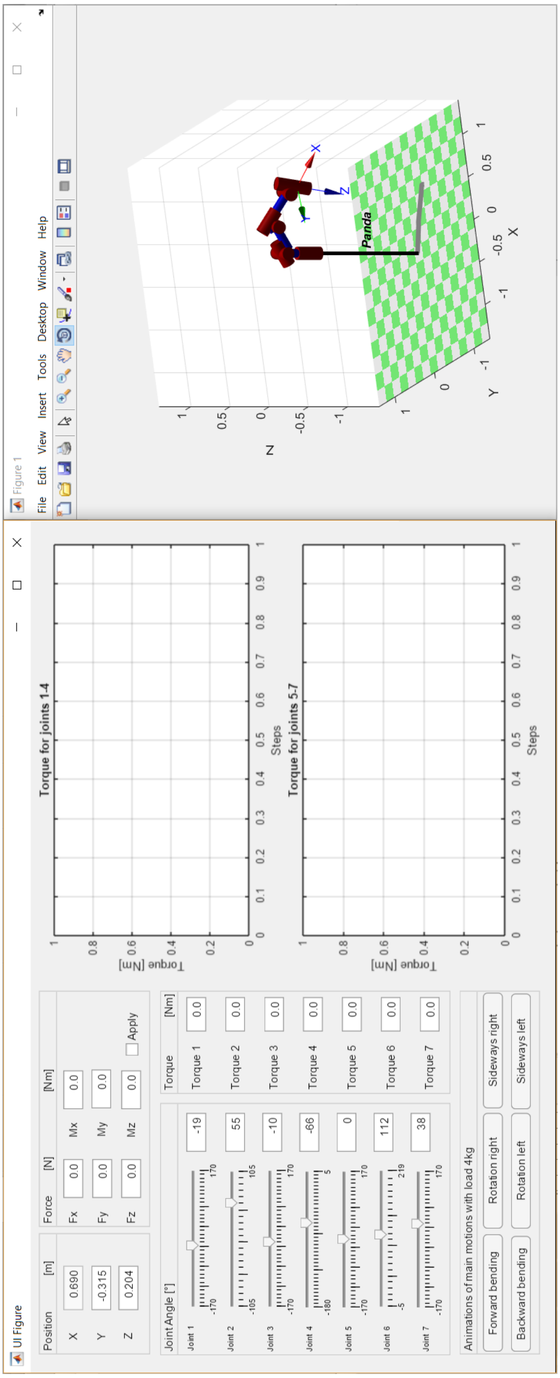


Appendix B

Motion platform - Computer model

Motion platform

Interface using sliders



Position [m]
X 0.690
Y -0.315
Z 0.204

Force [N]
Fx 0.0
Fy 0.0
Fz 0.0

[Nm]
Mx 0.0
My 0.0
Mz 0.0

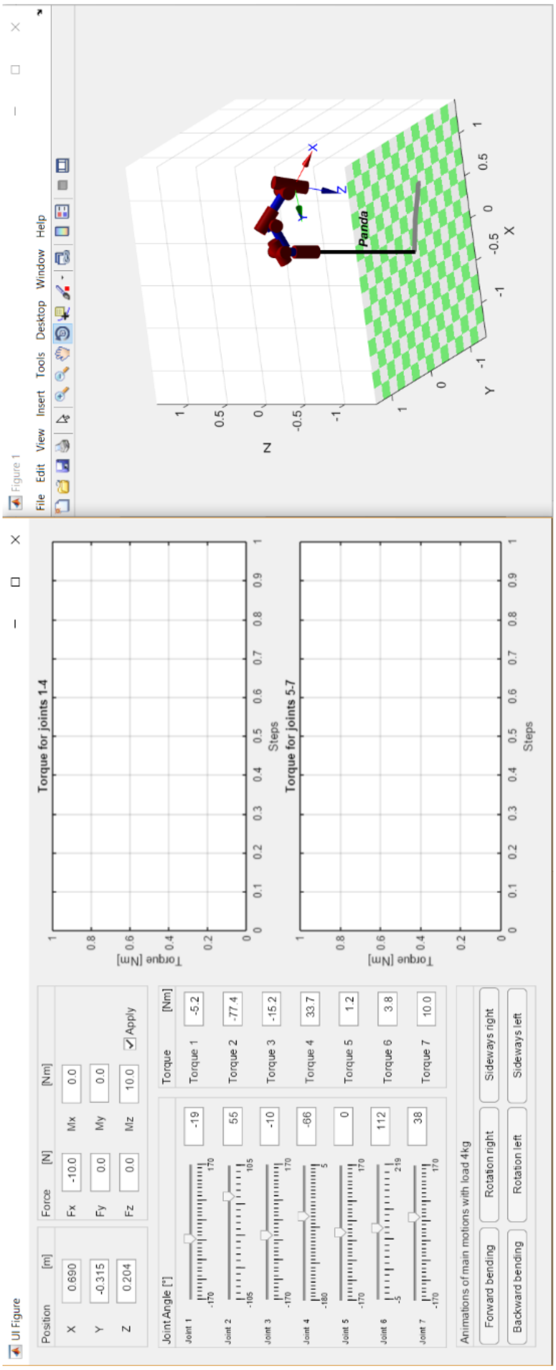
☐ Apply

Joint Angle [°]
Joint 1 -19
Joint 2 55
Joint 3 -10
Joint 4 -66
Joint 5 0
Joint 6 112
Joint 7 38

Torque [Nm]
Torque 1 0.0
Torque 2 0.0
Torque 3 0.0
Torque 4 0.0
Torque 5 0.0
Torque 6 0.0
Torque 7 0.0

Animations of main motions with load 4kg

Interface using force and torque



Position [m]
X 0.690
Y -0.315
Z 0.204

Force [N]
Fx -10.0
Fy 0.0
Fz 0.0

[Nm]
Mx 0.0
My 0.0
Mz 10.0

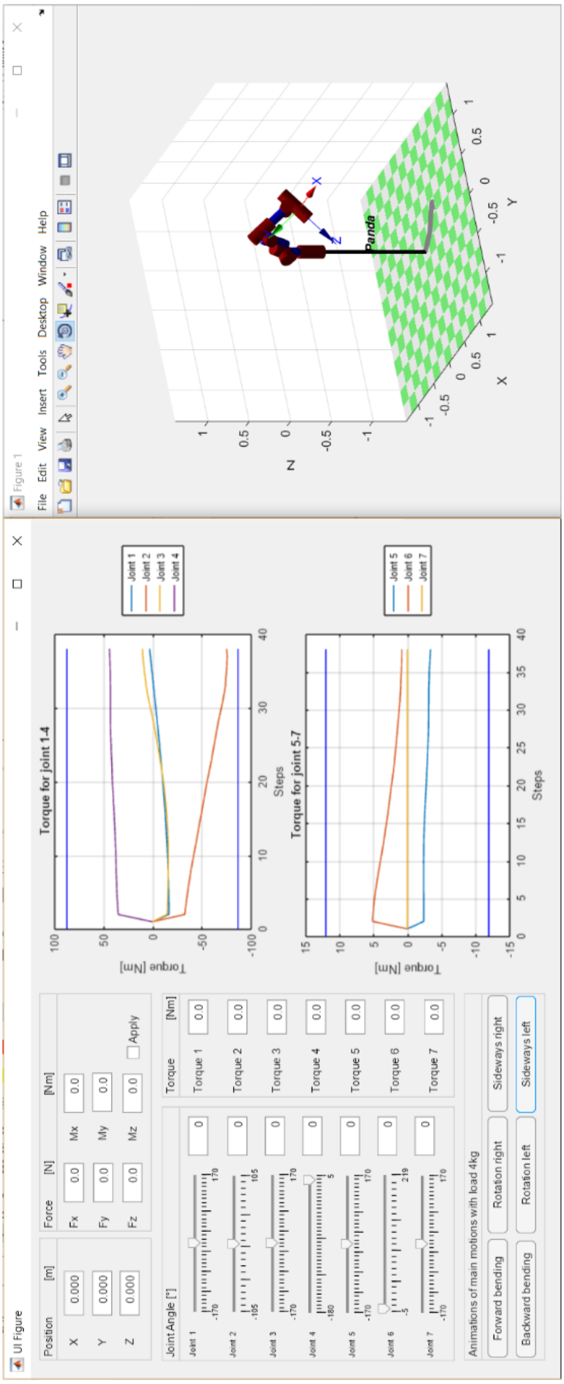
☑ Apply

Joint Angle [°]
Joint 1 -19
Joint 2 55
Joint 3 -10
Joint 4 -66
Joint 5 0
Joint 6 112
Joint 7 38

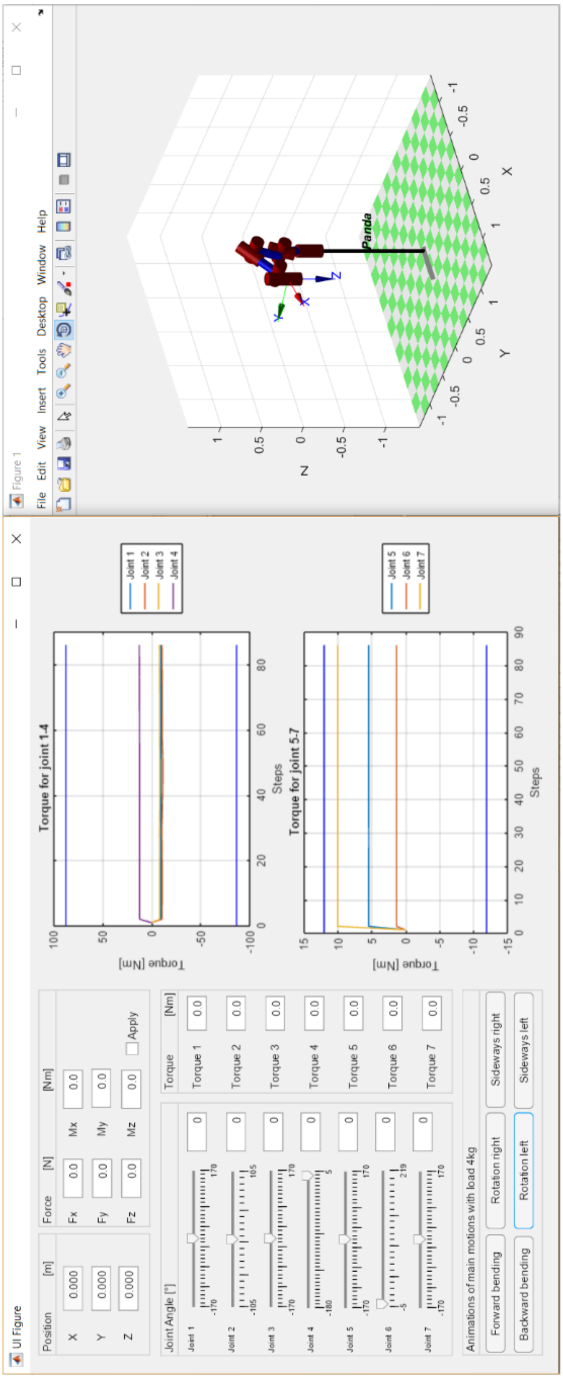
Torque [Nm]
Torque 1 -5.2
Torque 2 -77.4
Torque 3 -15.2
Torque 4 33.7
Torque 5 1.2
Torque 6 3.8
Torque 7 10.0

Animations of main motions with load 4kg

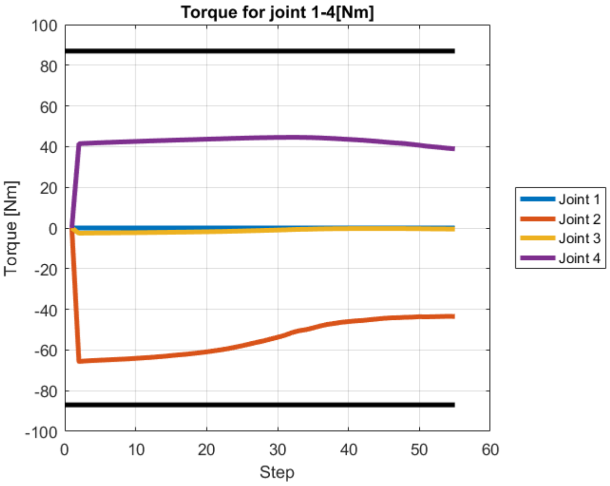
Interface using “Sideways left”

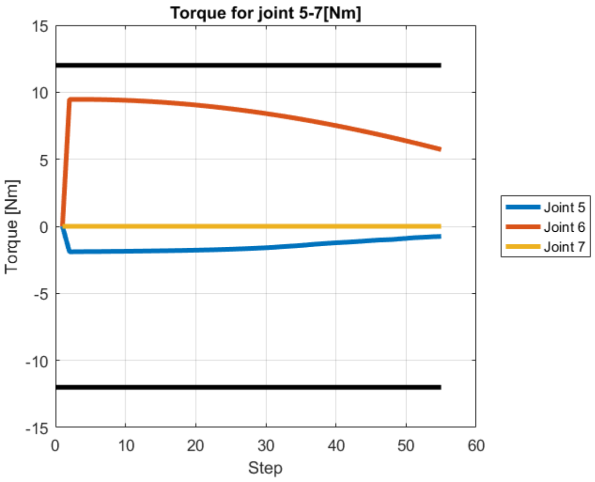


Interface using “Rotation left”

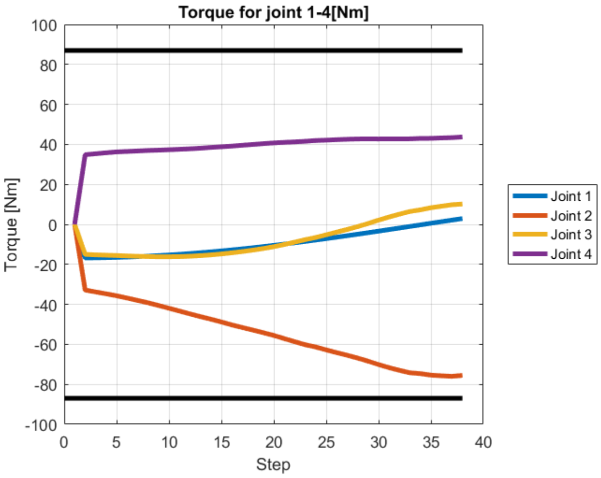


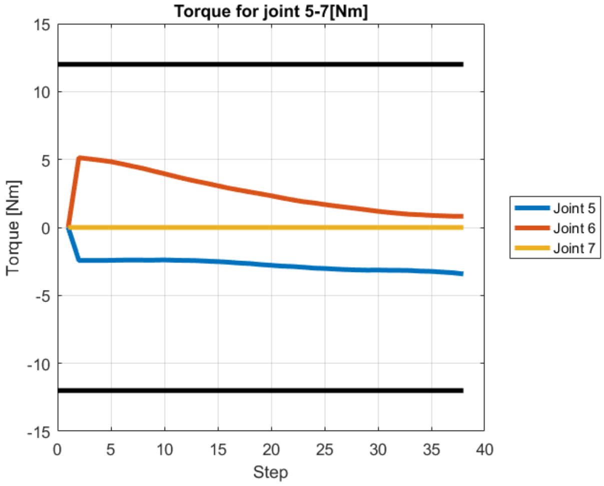
Torques during backward bending



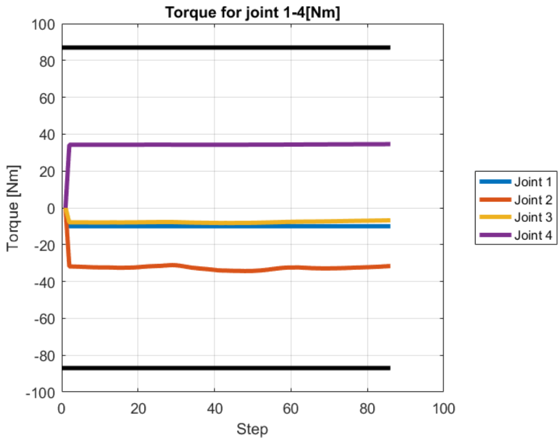


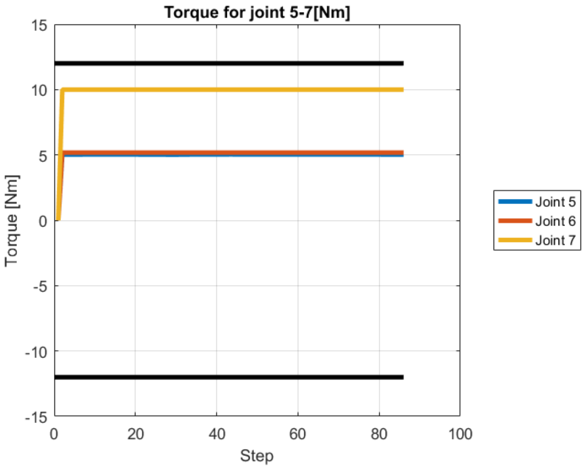
Torques during sideways rotation





Torques during rotational motion





Appendix C

Head mount - Workshop photos

Head mount

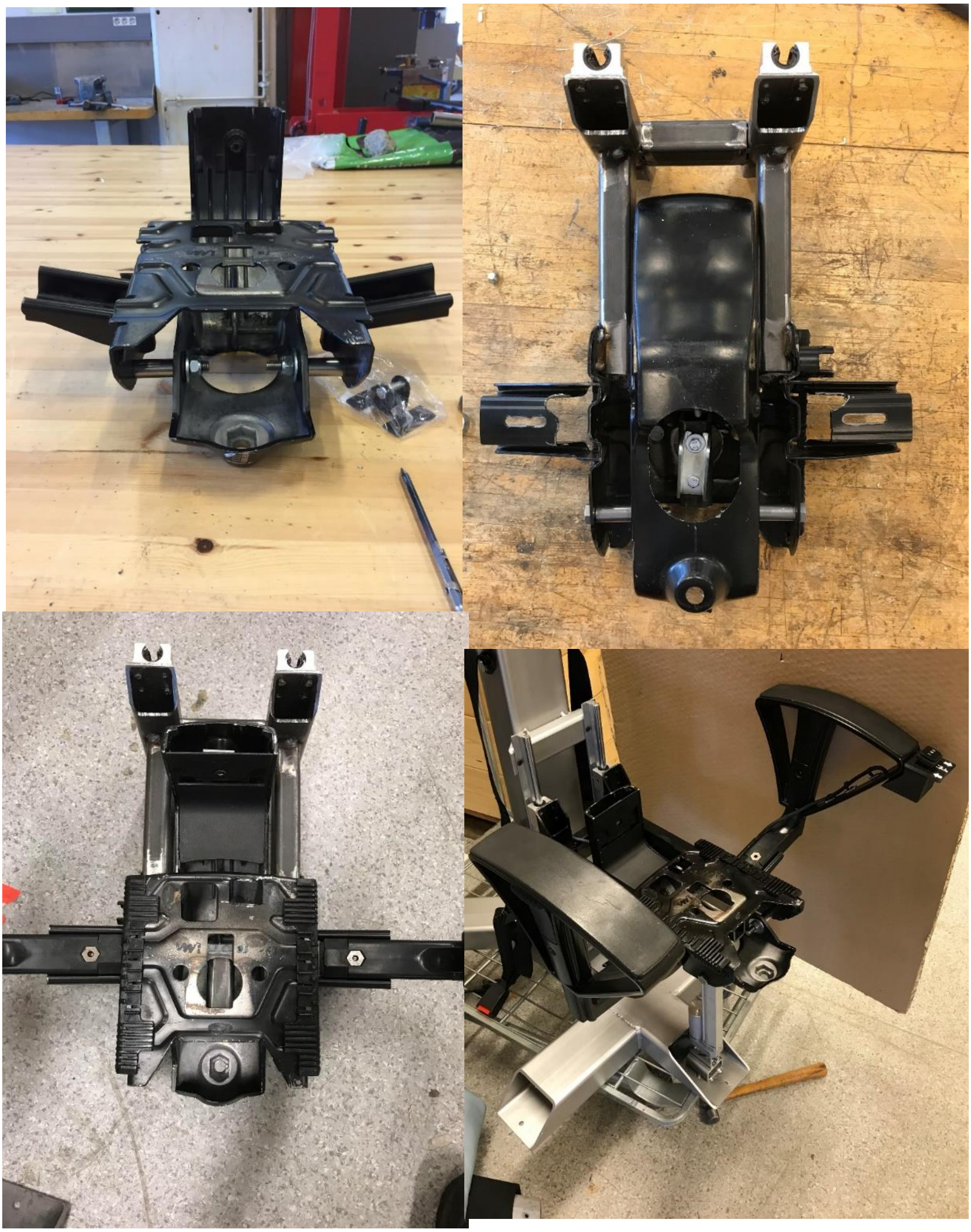

2
1
2
2
2
04
PE-LD


40
PE-LD

Appendix D

Chair - Workshop photos

Chair



Appendix E

Frame structure - Workshop photos

Frame structure


I O II

Appendix F

Accounting

Budget

	Item	NOK
1	Linear rails/bearing	408,24
2	Leveling feet	100,5
3	Four Point seatbelt	219,78
4	Bulb pump	55,83
5	Heatshrink	19,71
6	Linear actuator	330,23
7	Mounting brackets	28,59
8	PSU	72,55
9	Rocker switch	38,84
10	Wireclips	12,05
11	Spray paint	158
12	Faux leather	240
13	Kinnarps 6000 chair	Provided
14	120x80x5 RHS	Provided
15	50x30x4 RHS	Provided
SUM		1684,32

Appendix G

Computer code

Matlab Code

[1] Model of Panda with GUI

```
classdef AppDesignerRobot < matlab.apps.AppBase

% Properties that correspond to app components
properties (Access = public)
UIFigure                matlab.ui.Figure
PositionmPanel          matlab.ui.container.Panel
XEditFieldLabel         matlab.ui.control.Label
efPositionX             matlab.ui.control.NumericEditField
YEditFieldLabel         matlab.ui.control.Label
efPositionY             matlab.ui.control.NumericEditField
ZEditFieldLabel         matlab.ui.control.Label
efPositionZ             matlab.ui.control.NumericEditField
JointAnglePanel         matlab.ui.container.Panel
Joint1SliderLabel       matlab.ui.control.Label
sliderJoint1            matlab.ui.control.Slider
Joint2SliderLabel       matlab.ui.control.Label
sliderJoint2            matlab.ui.control.Slider
Joint3SliderLabel       matlab.ui.control.Label
sliderJoint3            matlab.ui.control.Slider
Joint4SliderLabel       matlab.ui.control.Label
sliderJoint4            matlab.ui.control.Slider
Joint5SliderLabel       matlab.ui.control.Label
sliderJoint5            matlab.ui.control.Slider
Joint6SliderLabel       matlab.ui.control.Label
sliderJoint6            matlab.ui.control.Slider
```

```
Joint7SliderLabel         matlab.ui.control.Label
sliderJoint7              matlab.ui.control.Slider
efSlider1                 matlab.ui.control.NumericEditField
efSlider2                 matlab.ui.control.NumericEditField
efSlider3                 matlab.ui.control.NumericEditField
efSlider4                 matlab.ui.control.NumericEditField
efSlider5                 matlab.ui.control.NumericEditField
efSlider6                 matlab.ui.control.NumericEditField
efSlider7                 matlab.ui.control.NumericEditField
TorqueNmPanel             matlab.ui.container.Panel
Torque1EditFieldLabel     matlab.ui.control.Label
efT1                      matlab.ui.control.NumericEditField
Torque2EditFieldLabel     matlab.ui.control.Label
efT2                      matlab.ui.control.NumericEditField
Torque4EditFieldLabel     matlab.ui.control.Label
efT4                      matlab.ui.control.NumericEditField
Torque3EditFieldLabel     matlab.ui.control.Label
efT3                      matlab.ui.control.NumericEditField
Torque5EditFieldLabel     matlab.ui.control.Label
efT5                      matlab.ui.control.NumericEditField
Torque6EditFieldLabel     matlab.ui.control.Label
efT6                      matlab.ui.control.NumericEditField
Torque7EditFieldLabel     matlab.ui.control.Label
efT7                      matlab.ui.control.NumericEditField
ForceNNmPanel             matlab.ui.container.Panel
FxEditFieldLabel          matlab.ui.control.Label
efForceX                  matlab.ui.control.NumericEditField
FyEditFieldLabel          matlab.ui.control.Label
efForceY                  matlab.ui.control.NumericEditField
FzEditFieldLabel          matlab.ui.control.Label
efForceZ                  matlab.ui.control.NumericEditField
MxEditFieldLabel          matlab.ui.control.Label
efMomentX                 matlab.ui.control.NumericEditField
MyEditFieldLabel          matlab.ui.control.Label
efMomentY                 matlab.ui.control.NumericEditField
MzEditFieldLabel          matlab.ui.control.Label
efMomentZ                 matlab.ui.control.NumericEditField
cbApplyForce              matlab.ui.control.CheckBox
axesPlot14                matlab.ui.control.UIAxes
Animationsofmainmotionswithload4kgPanel   matlab.ui.
    container.Panel
btnAroundFY               matlab.ui.control.Button
btnAroundBY               matlab.ui.control.Button
btnAroundRZ               matlab.ui.control.Button
btnAroundLZ               matlab.ui.control.Button
```

```
btnAroundRX                 matlab.ui.control.Button
btnAroundLX                 matlab.ui.control.Button
axesPlot57                  matlab.ui.control.UIAxes
end


properties (Access = private)
%Global variables
Robot % The model of the robotic arm
end


methods (Access = private)
%prints end position of the robot
function results = printPosition(app)
    endPosition = (app.Robot.fkine(app.Robot.getpos));
    endPosition = endPosition.T;
    app.efPositionX.Value = endPosition(1,4);
    app.efPositionY.Value = endPosition(2,4);
    app.efPositionZ.Value = endPosition(3,4);

end

%prints torques in each joint
function results = printTorque(app)
    fx = app.efForceX.Value;
    fy = app.efForceY.Value;
    fz = app.efForceZ.Value;
    mx = app.efMomentX.Value;
    my = app.efMomentY.Value;
    mz = app.efMomentZ.Value;

    torque = app.Robot.rne([app.Robot.getpos], [0 0 0 0 0 0 0 0], [0 0 0 0 0 0 0 0], 'fext', [fx fy fz mx my mz]);
    app.efT1.Value = torque(1);
    app.efT2.Value = torque(2);
    app.efT3.Value = torque(3);
    app.efT4.Value = torque(4);
    app.efT5.Value = torque(5);
    app.efT6.Value = torque(6);
    app.efT7.Value = torque(7);
end
end

```

```

methods (Access = private)

% Code that executes after component creation
function startupFcn(app)
    %builds the robot when the program is opened
    deg = pi/180;

    %DH-parameters
    L(1) = Revolute('a',0,      'd', 0.333, 'alpha',-pi/2);
    L(2) = Revolute('a',0,      'd', 0,     'alpha',pi/2);
    L(3) = Revolute('a',0.088, 'd', 0.316, 'alpha',pi/2);
    L(4) = Revolute('a',-0.088,'d', 0,     'alpha',-pi/2);
    L(5) = Revolute('a',0,      'd', 0.384, 'alpha',pi/2);
    L(6) = Revolute('a',0.088, 'd', 0,     'alpha',pi/2);
    L(7) = Revolute('a',0,      'd', 0.107, 'alpha',0);

    %joint angle limits
    L(1).qlim = [-170 170]*deg;
    L(2).qlim = [-150 150]*deg;
    L(3).qlim = [-170 170]*deg;
    L(4).qlim = [-180 5]*deg;
    L(5).qlim = [-170 170]*deg;
    L(6).qlim = [-5 220]*deg;
    L(7).qlim = [-170 170]*deg;
    L(8).qlim = [-180 180]*deg;

    %inertia matrix for each link
    L(1).I = (Imatrix(1,0.1,0.2,0.140,'rectangle'));
    L(2).I = (Imatrix(1,0.133,0.113,0.193,'cylinder'));
    L(3).I = (Imatrix(1,0.133,0.133,0.303,'cylinder'));
    L(4).I = (Imatrix(1,0.11,0.11,0.210,'cylinder'));
    L(5).I = (Imatrix(1,0.1,0.1,0.35,'cylinder'));
    L(6).I = (Imatrix(1,0.095,0.095,0.18,'cylinder'));
    L(7).I = (Imatrix(1,0.088,0.088,0.136,'cylinder'));
    L(8).I = (Imatrix(1,0.088,0.088,0.054,'cylinder'));

    %mass
    L(1).m = (3);
    L(2).m = (3);
    L(3).m = (3);
    L(4).m = (3);
    L(5).m = (2);
    L(6).m = (2);
    L(7).m = (2);
```

```
    L(8).m = (2);

    %distance of center of mass relativ to reference frame
       of link
    L(1).r = ([0,0,0.14/2]);
    L(2).r = ([0,0.193/2,0]);
    L(3).r = ([0,0,0.303/2]);
    L(4).r = ([0,0,0]);
    L(5).r = ([0,0,0.35/2]);
    L(6).r = ([0,0,0]);
    L(7).r = ([0,0,0]);
    L(8).r = ([0,0,-0.054/2]);

    %connect links to a chain
    app.Robot = SerialLink(L, 'name', 'Panda');
    %plot model in position where all joint angels = 0
    app.Robot.plot([0 0 0 0 0 0 0 0]);
end

% Callback function: efPositionX, sliderJoint1
function Joint1SliderValueChanging(app, event)
    %change position of joint 1 when slider 1 is moved
    changingValueq1 = event.Value;
    q2 = app.sliderJoint2.Value;
    q3 = app.sliderJoint3.Value;
    q4 = app.sliderJoint4.Value;
    q5 = app.sliderJoint5.Value;
    q6 = app.sliderJoint6.Value;
    q7 = app.sliderJoint7.Value;

    app.efSlider1.Value = floor(event.Value);
    app.Robot.plot([changingValueq1 q2 q3 q4 q5 q6 q7 0]*pi
       /180);
    app.printPosition();
    %if the apply force box is ticked of the torques are
       calculated
    if app.cbApplyForce.Value
        app.printTorque();
    end
end

% Value changing function: sliderJoint2
function sliderJoint2ValueChanging(app, event)
    %change position of joint 2 when slider 2 is moved
    changingValueq2 = event.Value;
```

```
    q1 = app.sliderJoint1.Value;
    q3 = app.sliderJoint3.Value;
    q4 = app.sliderJoint4.Value;
    q5 = app.sliderJoint5.Value;
    q6 = app.sliderJoint6.Value;
    q7 = app.sliderJoint7.Value;

    app.efSlider2.Value = floor(event.Value);
    app.Robot.plot([q1 changingValueq2 q3 q4 q5 q6 q7 0]*pi/180);
    app.printPosition();
    %if the apply force box is ticked of the torques are calculated
    if app.cbApplyForce.Value
        app.printTorque();
    end
end

% Value changing function: sliderJoint3
function sliderJoint3ValueChanging(app, event)
    %change position of joint 3 when slider 3 is moved
    changingValueq3 = event.Value;
    q1 = app.sliderJoint1.Value;
    q2 = app.sliderJoint2.Value;
    q4 = app.sliderJoint4.Value;
    q5 = app.sliderJoint5.Value;
    q6 = app.sliderJoint6.Value;
    q7 = app.sliderJoint7.Value;

    app.efSlider3.Value = floor(event.Value);
    app.Robot.plot([q1 q2 changingValueq3 q4 q5 q6 q7 0]*pi/180);
    app.printPosition();
    %if the apply force box is ticked of the torques are calculated
    if app.cbApplyForce.Value
        app.printTorque();
    end
end

% Value changing function: sliderJoint4
function sliderJoint4ValueChanging(app, event)
    %change position of joint 4 when slider 4 is moved
    changingValueq4 = event.Value;
    q1 = app.sliderJoint1.Value;
```

```
    q2 = app.sliderJoint2.Value;
    q3 = app.sliderJoint3.Value;
    q5 = app.sliderJoint5.Value;
    q6 = app.sliderJoint6.Value;
    q7 = app.sliderJoint7.Value;

    app.efSlider4.Value = floor(event.Value);
    app.Robot.plot([q1 q2 q3 changingValueq4 q5 q6 q7 0]*pi
        /180);
    app.printPosition();
    %if the apply force box is ticked of the torques are
        calculated
    if app.cbApplyForce.Value
        app.printTorque();
    end
end

% Value changing function: sliderJoint5
function sliderJoint5ValueChanging(app, event)
    changingValueq5 = event.Value;
    q1 = app.sliderJoint1.Value;
    q2 = app.sliderJoint2.Value;
    q3 = app.sliderJoint3.Value;
    q4 = app.sliderJoint4.Value;
    q6 = app.sliderJoint6.Value;
    q7 = app.sliderJoint7.Value;

    app.efSlider5.Value = floor(event.Value);
    app.Robot.plot([q1 q2 q3 q4 changingValueq5 q6 q7 0]*pi
        /180);
    app.printPosition();
    if app.cbApplyForce.Value
        app.printTorque();
    end
end

% Value changing function: sliderJoint6
function sliderJoint6ValueChanging(app, event)
    %change position of joint 6 when slider 6 is moved
    changingValueq6 = event.Value;
    q1 = app.sliderJoint1.Value;
    q2 = app.sliderJoint2.Value;
    q3 = app.sliderJoint3.Value;
    q4 = app.sliderJoint4.Value;
    q5 = app.sliderJoint5.Value;
```

```
    q7 = app.sliderJoint7.Value;

    app.efSlider6.Value = floor(event.Value);
    app.Robot.plot([q1 q2 q3 q4 q5 changingValueq6 q7 0]*pi/180);
    app.printPosition();
    %if the apply force box is ticked of the torques are calculated
    if app.cbApplyForce.Value
        app.printTorque();
    end
end

% Value changing function: sliderJoint7
function sliderJoint7ValueChanging(app, event)
    %change position of joint 1 when slider 1 is moved
    changingValueq7 = event.Value;
    q1 = app.sliderJoint1.Value;
    q2 = app.sliderJoint2.Value;
    q3 = app.sliderJoint3.Value;
    q4 = app.sliderJoint4.Value;
    q5 = app.sliderJoint5.Value;
    q6 = app.sliderJoint6.Value;

    app.efSlider7.Value = floor(event.Value);
    app.Robot.plot([q1 q2 q3 q4 q5 q6 changingValueq7 0]*pi/180);
    app.printPosition();
    %if the apply force box is ticked of the torques are calculated
    if app.cbApplyForce.Value
        app.printTorque();
    end
end

% Value changed function: cbApplyForce
function cbApplyForceValueChanged(app, event)
    %when ”Apply force” is ticked of the torques are calculated.
    %If not the forces are set to 0
    value = app.cbApplyForce.Value;
    if value
        app.printTorque();
    else
        app.efForceX.Value = 0;
```

```
        app.efForceY.Value = 0;
        app.efForceZ.Value = 0;
        app.efMomentX.Value = 0;
        app.efMomentY.Value = 0;
        app.efMomentZ.Value = 0;
    end
end

% Value changed function: efForceX
function efForceXValueChanged(app, event)
    %when force in x-direction is changed the torques are
        updated
    value = app.efForceX.Value;
    if app.cbApplyForce.Value
        app.printTorque();
    end
end

% Value changed function: efForceY
function efForceYValueChanged(app, event)
    %when force in y-direction is changed the torques are
        updated
    value = app.efForceY.Value;
    if app.cbApplyForce.Value
        app.printTorque();
    end
end

% Value changed function: efForceZ
function efForceZValueChanged(app, event)
    %when force in z-direction is changed the torques are
        updated
    value = app.efForceZ.Value;
    if app.cbApplyForce.Value
        app.printTorque();
    end
end

% Value changed function: efMomentX
function efMomentXValueChanged(app, event)
    %when momentum in x-direction is changed the torques
        are updated
    value = app.efMomentX.Value;
    if app.cbApplyForce.Value
        app.printTorque();
```

```
    end
end

% Value changed function: efMomentY
function efMomentYValueChanged(app, event)
    %when momentum in y-direction is changed the torques
        are updated
    value = app.efMomentY.Value;
    if app.cbApplyForce.Value
        app.printTorque();
    end
end

% Value changed function: efMomentZ
function efMomentZValueChanged(app, event)
    %when momentum in z-direction is changed the torques
        are updated
    value = app.efMomentZ.Value;
    if app.cbApplyForce.Value
        app.printTorque();
    end
end

% Value changed function: efSlider1
function efSlider1ValueChanged(app, event)
    %angle of joint 1 is changed based on input field
    value = app.efSlider1.Value;
    position = app.Robot.getpos();
    position(1) = value*(pi/180);
    app.sliderJoint1.Value = value;
    app.Robot.plot(position);
end

% Value changed function: efSlider2
function efSlider2ValueChanged(app, event)
    %angle of joint 2 is changed based on input field
    value = app.efSlider2.Value;
    position = app.Robot.getpos();
    position(2) = value*(pi/180);
    app.sliderJoint2.Value = value;
    app.Robot.plot(position);
end

% Value changed function: efSlider3
function efSlider3ValueChanged(app, event)
```

```
    %angle of joint 3 is changed based on input field
    value = app.efSlider3.Value;
    position = app.Robot.getpos();
    position(3) = value*(pi/180);
    app.sliderJoint3.Value = value*(180/pi);
    app.Robot.plot(position);

end

% Value changed function: efSlider4
function efSlider4ValueChanged(app, event)
    %angle of joint 4 is changed based on input field
    value = app.efSlider4.Value;
    position = app.Robot.getpos();
    position(4) = value*(pi/180);
    app.sliderJoint4.Value = value;
    app.Robot.plot(position);

end

% Value changed function: efSlider5
function efSlider5ValueChanged(app, event)
    %angle of joint 5 is changed based on input field
    value = app.efSlider5.Value;
    position = app.Robot.getpos();
    position(5) = value*(pi/180);
    app.sliderJoint5.Value = value;
    app.Robot.plot(position);
end

% Value changed function: efSlider6
function efSlider6ValueChanged(app, event)
    %angle of joint 6 is changed based on input field
    value = app.efSlider6.Value;
    position = app.Robot.getpos();
    position(6) = value*(pi/180);
    app.sliderJoint6.Value = value;
    app.Robot.plot(position);
end

% Value changed function: efSlider7
function efSlider7ValueChanged(app, event)
    %angle of joint 7 is changed based on input field
    value = app.efSlider7.Value;
    position = app.Robot.getpos();
```

```matlab
    position(7) = value*(pi/180);
    app.sliderJoint7.Value = value;
    app.Robot.plot(position);
end

% Button pushed function: btnAroundFY
function btnAroundFYButtonPushed(app, event)
    %Forward bending
    load('Q_f_y.mat') %Matrix with joint space vectors for each step
    Q = [Q; flipud(Q)];
    load('torque_f_y.mat') %Matrix with torque loads for each step

    %2D-plots are cleared
    ax14 = app.axesPlot14;
    ax57 = app.axesPlot57;
    cla(ax14)
    cla(ax57)

    %torques are plotted
    title(ax14,'Torque for joint 1-4')
    plot(ax14,torque(:,1:4))
    hold(ax14,'on')
    plot(ax14, [0 length(torque(:,1))], [87 87], 'b')
    plot(ax14, [0 length(torque(:,1))], [-87 -87], 'b')
    grid(ax14,'on')
    legend(ax14, 'Joint 1', 'Joint 2', 'Joint 3', 'Joint 4', 'Location', 'eastoutside');
    xlabel(ax14, 'Steps')
    ylabel(ax14, 'Torque [Nm]')

    title(ax57,'Torque for joint 5-7')
    plot(ax57,torque(:,5:7))
    hold(ax57,'on')
    plot(ax57, [0 length(torque(:,1))], [12 12], 'b')
    plot(ax57, [0 length(torque(:,1))], [-12 -12], 'b')
    grid(ax57,'on')
    legend(ax57, 'Joint 5', 'Joint 6', 'Joint 7', 'Location', 'eastoutside');
    xlabel(ax57, 'Steps')
    ylabel(ax57, 'Torque [Nm]')

    %the motion is animated
    app.Robot.animate(Q)
```

```
end

% Button pushed function: btnAroundBY
function btnAroundBYButtonPushed(app, event)
    %Backward bending
    load('Q_b_y.mat') %Matrix with joint space vectors for each step
    Q = [Q; flipud(Q)];
    load('torque_b_y.mat') %Matrix with torque loads for each step

    %2D-plots are cleared
    ax14 = app.axesPlot14;
    ax57 = app.axesPlot57;
    cla(ax14)
    cla(ax57)

    %torques are plotted
    title(ax14,'Torque for joint 1-4')
    plot(ax14,torque(:,1:4))
    hold(ax14,'on')
    plot(ax14, [0 length(torque(:,1))], [87 87], 'b')
    plot(ax14, [0 length(torque(:,1))], [-87 -87], 'b')
    grid(ax14,'on')
    legend(ax14, 'Joint 1', 'Joint 2', 'Joint 3', 'Joint 4', 'Location', 'eastoutside');
    xlabel(ax14, 'Steps')
    ylabel(ax14, 'Torque [Nm]')

    title(ax57,'Torque for joint 5-7')
    plot(ax57,torque(:,5:7))
    hold(ax57,'on')
    plot(ax57, [0 length(torque(:,1))], [12 12], 'b')
    plot(ax57, [0 length(torque(:,1))], [-12 -12], 'b')
    grid(ax57,'on')
    legend(ax57, 'Joint 5', 'Joint 6', 'Joint 7', 'Location', 'eastoutside');
    xlabel(ax57, 'Steps')
    ylabel(ax57, 'Torque [Nm]')

    %the motion is animated
    app.Robot.animate(Q)
end

% Button pushed function: btnAroundRZ
```

```matlab
function btnAroundRZButtonPushed(app, event)
    %Rotation to the right
    load('Q_r_z.mat') %Matrix with joint space vectors for each step
    Q = [Q; flipud(Q)];
    load('torque_r_z.mat') %Matrix with torque loads for each step

    %2D-plots are cleared
    ax14 = app.axesPlot14;
    ax57 = app.axesPlot57;
    cla(ax14)
    cla(ax57)

    %torques are plotted
    title(ax14,'Torque for joint 1-4')
    plot(ax14,torque(:,1:4))
    hold(ax14,'on')
    plot(ax14, [0 length(torque(:,1))], [87 87], 'b')
    plot(ax14, [0 length(torque(:,1))], [-87 -87], 'b')
    grid(ax14,'on')
    legend(ax14, 'Joint 1', 'Joint 2', 'Joint 3', 'Joint 4', 'Location', 'eastoutside');
    xlabel(ax14, 'Steps')
    ylabel(ax14, 'Torque [Nm]')

    title(ax57,'Torque for joint 5-7')
    plot(ax57,torque(:,5:7))
    hold(ax57,'on')
    plot(ax57, [0 length(torque(:,1))], [12 12], 'b')
    plot(ax57, [0 length(torque(:,1))], [-12 -12], 'b')
    grid(ax57,'on')
    legend(ax57, 'Joint 5', 'Joint 6', 'Joint 7', 'Location', 'eastoutside');
    xlabel(ax57, 'Steps')
    ylabel(ax57, 'Torque [Nm]')

    %the motion is animated
    app.Robot.animate(Q)
end

% Button pushed function: btnAroundLZ
function btnAroundLZButtonPushed(app, event)
    %Rotation to the left
    load('Q_l_z.mat') %Matrix with joint space vectors for
```

```
        each step
    Q = [Q; flipud(Q)];
    load('torque_l_z.mat') %Matrix with torque loads for
        each step

    %2D-plots are cleared
    ax14 = app.axesPlot14;
    ax57 = app.axesPlot57;
    cla(ax14)
    cla(ax57)

    %torques are plotted
    title(ax14,'Torque for joint 1-4')
    plot(ax14,torque(:,1:4))
    hold(ax14,'on')
    plot(ax14, [0 length(torque(:,1))], [87 87], 'b')
    plot(ax14, [0 length(torque(:,1))], [-87 -87], 'b')
    grid(ax14,'on')
    legend(ax14, 'Joint 1', 'Joint 2', 'Joint 3', 'Joint 4'
        , 'Location', 'eastoutside');
    xlabel(ax14, 'Steps')
    ylabel(ax14, 'Torque [Nm]')

    title(ax57,'Torque for joint 5-7')
    plot(ax57,torque(:,5:7))
    hold(ax57,'on')
    plot(ax57, [0 length(torque(:,1))], [12 12], 'b')
    plot(ax57, [0 length(torque(:,1))], [-12 -12], 'b')
    grid(ax57,'on')
    legend(ax57, 'Joint 5', 'Joint 6', 'Joint 7', 'Location
        ', 'eastoutside');
    xlabel(ax57, 'Steps')
    ylabel(ax57, 'Torque [Nm]')

    %motion is animated
    app.Robot.animate(Q)
end

% Button pushed function: btnAroundRX
function btnAroundRXButtonPushed(app, event)
    %Sideways bending to the right
    load('Q_r_x.mat') %Matrix with joint space vectors for
        each step
    Q = [Q; flipud(Q)];
    load('torque_r_x.mat') %Matrix with torque loads for
```

```
        each step

    %2D-plots are cleared
    ax14 = app.axesPlot14;
    ax57 = app.axesPlot57;
    cla(ax14)
    cla(ax57)

    %torques are plotted
    title(ax14,'Torque for joint 1-4')
    plot(ax14,torque(:,1:4))
    hold(ax14,'on')
    plot(ax14, [0 length(torque(:,1))], [87 87], 'b')
    plot(ax14, [0 length(torque(:,1))], [-87 -87], 'b')
    grid(ax14,'on')
    legend(ax14, 'Joint 1', 'Joint 2', 'Joint 3', 'Joint 4'
        , 'Location', 'eastoutside');
    xlabel(ax14, 'Steps')
    ylabel(ax14, 'Torque [Nm]')

    title(ax57,'Torque for joint 5-7')
    plot(ax57,torque(:,5:7))
    hold(ax57,'on')
    plot(ax57, [0 length(torque(:,1))], [12 12], 'b')
    plot(ax57, [0 length(torque(:,1))], [-12 -12], 'b')
    grid(ax57,'on')
    legend(ax57, 'Joint 5', 'Joint 6', 'Joint 7', 'Location
        ', 'eastoutside');
    xlabel(ax57, 'Steps')
    ylabel(ax57, 'Torque [Nm]')

    %motion is animated
    app.Robot.animate(Q)
end

% Button pushed function: btnAroundLX
function btnAroundLXButtonPushed(app, event)
    %Sideways bending to the left
    load('Q_l_x.mat') %Matrix with joint space vectors for
        each step
    Q = [Q; flipud(Q)];
    load('torque_l_x.mat') %Matrix with torque loads for
        each step

    %2D-plots are cleard
```

```
    ax14 = app.axesPlot14;
    ax57 = app.axesPlot57;
    cla(ax14)
    cla(ax57)

    %torques are plotted
    title(ax14,'Torque for joint 1-4')
    plot(ax14,torque(:,1:4))
    hold(ax14,'on')
    plot(ax14, [0 length(torque(:,1))], [87 87], 'b')
    plot(ax14, [0 length(torque(:,1))], [-87 -87], 'b')
    grid(ax14,'on')
    legend(ax14, 'Joint 1', 'Joint 2', 'Joint 3', 'Joint 4', 'Location', 'eastoutside');
    xlabel(ax14, 'Steps')
    ylabel(ax14, 'Torque [Nm]')

    title(ax57,'Torque for joint 5-7')
    plot(ax57,torque(:,5:7))
    hold(ax57,'on')
    plot(ax57, [0 length(torque(:,1))], [12 12], 'b')
    plot(ax57, [0 length(torque(:,1))], [-12 -12], 'b')
    grid(ax57,'on')
    legend(ax57, 'Joint 5', 'Joint 6', 'Joint 7', 'Location', 'eastoutside');
    xlabel(ax57, 'Steps')
    ylabel(ax57, 'Torque [Nm]')

    %motion is animated
    app.Robot.animate(Q)
end
end

% App initialization and construction
methods (Access = private)

% Create UIFigure and components
function createComponents(app)

    % Create UIFigure
    app.UIFigure = uifigure;
    app.UIFigure.Position = [100 100 942 581];
    app.UIFigure.Name = 'UI Figure';
    setAutoResize(app, app.UIFigure, true)

```

```
        % Create PositionmPanel
        app.PositionmPanel = uipanel(app.UIFigure);
        app.PositionmPanel.Title = 'Position              [m] ';
        app.PositionmPanel.Position = [21 449 134 123];

        % Create XEditFieldLabel
        app.XEditFieldLabel = uilabel(app.PositionmPanel);
        app.XEditFieldLabel.HorizontalAlignment = 'right';
        app.XEditFieldLabel.Position = [9 78 15 15];
        app.XEditFieldLabel.Text = 'X';

        % Create efPositionX
        app.efPositionX = uieditfield(app.PositionmPanel, 'numeric');
        app.efPositionX.ValueChangedFcn = createCallbackFcn(app, @Joint1SliderValueChanging, true);
        app.efPositionX.ValueDisplayFormat = '%.3f';
        app.efPositionX.Editable = 'off';
        app.efPositionX.Position = [49 74 49 22];

        % Create YEditFieldLabel
        app.YEditFieldLabel = uilabel(app.PositionmPanel);
        app.YEditFieldLabel.HorizontalAlignment = 'right';
        app.YEditFieldLabel.Position = [-1 47 25 15];
        app.YEditFieldLabel.Text = 'Y';

        % Create efPositionY
        app.efPositionY = uieditfield(app.PositionmPanel, 'numeric');
        app.efPositionY.ValueDisplayFormat = '%.3f';
        app.efPositionY.Position = [49 43 49 22];

        % Create ZEditFieldLabel
        app.ZEditFieldLabel = uilabel(app.PositionmPanel);
        app.ZEditFieldLabel.HorizontalAlignment = 'right';
        app.ZEditFieldLabel.Position = [-1 17 25 15];
        app.ZEditFieldLabel.Text = 'Z';

        % Create efPositionZ
        app.efPositionZ = uieditfield(app.PositionmPanel, 'numeric');
        app.efPositionZ.ValueDisplayFormat = '%.3f';
        app.efPositionZ.Position = [49 13 49 22];

        % Create JointAnglePanel
```

```
    app.JointAnglePanel = uipanel(app.UIFigure);
    app.JointAnglePanel.Title = 'Joint Angle [ ]';
    app.JointAnglePanel.Position = [20 117 279 321];

    % Create Joint1SliderLabel
    app.Joint1SliderLabel = uilabel(app.JointAnglePanel);
    app.Joint1SliderLabel.HorizontalAlignment = 'right';
    app.Joint1SliderLabel.FontSize = 9;
    app.Joint1SliderLabel.Position = [0 277 33 15];
    app.Joint1SliderLabel.Text = 'Joint 1';

    % Create sliderJoint1
    app.sliderJoint1 = uislider(app.JointAnglePanel);
    app.sliderJoint1.Limits = [-170 170];
    app.sliderJoint1.MajorTicks = [-170 -120 -70 -20 30 80 170];
    app.sliderJoint1.MajorTickLabels = {'-170', '', '', '', '', '', '170'};
    app.sliderJoint1.ValueChangingFcn = createCallbackFcn(app, @Joint1SliderValueChanging, true);
    app.sliderJoint1.FontSize = 9;
    app.sliderJoint1.Position = [54 283 150 3];

    % Create Joint2SliderLabel
    app.Joint2SliderLabel = uilabel(app.JointAnglePanel);
    app.Joint2SliderLabel.HorizontalAlignment = 'right';
    app.Joint2SliderLabel.FontSize = 9;
    app.Joint2SliderLabel.Position = [-1 233 33 15];
    app.Joint2SliderLabel.Text = 'Joint 2';

    % Create sliderJoint2
    app.sliderJoint2 = uislider(app.JointAnglePanel);
    app.sliderJoint2.Limits = [-105 105];
    app.sliderJoint2.MajorTicks = [-105 -55 -5 45 105];
    app.sliderJoint2.MajorTickLabels = {'-105', '', '', '', '105'};
    app.sliderJoint2.ValueChangingFcn = createCallbackFcn(app, @sliderJoint2ValueChanging, true);
    app.sliderJoint2.FontSize = 9;
    app.sliderJoint2.Position = [54 240 149 3];

    % Create Joint3SliderLabel
    app.Joint3SliderLabel = uilabel(app.JointAnglePanel);
    app.Joint3SliderLabel.HorizontalAlignment = 'right';
    app.Joint3SliderLabel.FontSize = 9;
```

```
            app.Joint3SliderLabel.Position = [-1 189 33 15];
            app.Joint3SliderLabel.Text = 'Joint 3';

            % Create sliderJoint3
            app.sliderJoint3 = uislider(app.JointAnglePanel);
            app.sliderJoint3.Limits = [-170 170];
            app.sliderJoint3.MajorTicks = [-170 -120 -70 -20 30 80 170];
            app.sliderJoint3.MajorTickLabels = {'-170', '', '', '', '', '', '170'};
            app.sliderJoint3.ValueChangingFcn = createCallbackFcn(app, @sliderJoint3ValueChanging, true);
            app.sliderJoint3.FontSize = 9;
            app.sliderJoint3.Position = [54 198 150 3];

            % Create Joint4SliderLabel
            app.Joint4SliderLabel = uilabel(app.JointAnglePanel);
            app.Joint4SliderLabel.HorizontalAlignment = 'right';
            app.Joint4SliderLabel.FontSize = 9;
            app.Joint4SliderLabel.Position = [-1 146 33 15];
            app.Joint4SliderLabel.Text = 'Joint 4';

            % Create sliderJoint4
            app.sliderJoint4 = uislider(app.JointAnglePanel);
            app.sliderJoint4.Limits = [-180 5];
            app.sliderJoint4.MajorTicks = [-180 -130 -80 5];
            app.sliderJoint4.MajorTickLabels = {'-180', '', '', '5'};
            app.sliderJoint4.ValueChangingFcn = createCallbackFcn(app, @sliderJoint4ValueChanging, true);
            app.sliderJoint4.FontSize = 9;
            app.sliderJoint4.Position = [53 157 150 3];

            % Create Joint5SliderLabel
            app.Joint5SliderLabel = uilabel(app.JointAnglePanel);
            app.Joint5SliderLabel.HorizontalAlignment = 'right';
            app.Joint5SliderLabel.FontSize = 9;
            app.Joint5SliderLabel.Position = [-1 103 33 15];
            app.Joint5SliderLabel.Text = 'Joint 5';

            % Create sliderJoint5
            app.sliderJoint5 = uislider(app.JointAnglePanel);
            app.sliderJoint5.Limits = [-170 170];
            app.sliderJoint5.MajorTicks = [-170 -120 -70 -20 30 80 170];
```

```
        app.sliderJoint5.MajorTickLabels = {'-170', '', '', '', '', '', '170'};
        app.sliderJoint5.ValueChangingFcn = createCallbackFcn(app, @sliderJoint5ValueChanging, true);
        app.sliderJoint5.FontSize = 9;
        app.sliderJoint5.Position = [53 116 150 3];

        % Create Joint6SliderLabel
        app.Joint6SliderLabel = uilabel(app.JointAnglePanel);
        app.Joint6SliderLabel.HorizontalAlignment = 'right';
        app.Joint6SliderLabel.FontSize = 9;
        app.Joint6SliderLabel.Position = [-1 60 33 15];
        app.Joint6SliderLabel.Text = 'Joint 6';

        % Create sliderJoint6
        app.sliderJoint6 = uislider(app.JointAnglePanel);
        app.sliderJoint6.Limits = [-5 219];
        app.sliderJoint6.MajorTicks = [-5 45 95 145 219];
        app.sliderJoint6.MajorTickLabels = {'-5', '', '', '', '219'};
        app.sliderJoint6.ValueChangingFcn = createCallbackFcn(app, @sliderJoint6ValueChanging, true);
        app.sliderJoint6.FontSize = 9;
        app.sliderJoint6.Position = [54 75 150 3];

        % Create Joint7SliderLabel
        app.Joint7SliderLabel = uilabel(app.JointAnglePanel);
        app.Joint7SliderLabel.HorizontalAlignment = 'right';
        app.Joint7SliderLabel.FontSize = 9;
        app.Joint7SliderLabel.Position = [-1 17 33 15];
        app.Joint7SliderLabel.Text = 'Joint 7';

        % Create sliderJoint7
        app.sliderJoint7 = uislider(app.JointAnglePanel);
        app.sliderJoint7.Limits = [-170 170];
        app.sliderJoint7.MajorTicks = [-170 -120 -70 -20 30 80 170];
        app.sliderJoint7.MajorTickLabels = {'-170', '', '', '', '', '', '170'};
        app.sliderJoint7.ValueChangingFcn = createCallbackFcn(app, @sliderJoint7ValueChanging, true);
        app.sliderJoint7.FontSize = 9;
        app.sliderJoint7.Position = [53 34 150 3];

        % Create efSlider1
```

```
    app.efSlider1 = uieditfield(app.JointAnglePanel, '
        numeric');
    app.efSlider1.ValueChangedFcn = createCallbackFcn(app,
        @efSlider1ValueChanged, true);
    app.efSlider1.Position = [225 270 43 22];

    % Create efSlider2
    app.efSlider2 = uieditfield(app.JointAnglePanel, '
        numeric');
    app.efSlider2.ValueChangedFcn = createCallbackFcn(app,
        @efSlider2ValueChanged, true);
    app.efSlider2.Position = [225 227 43 22];

    % Create efSlider3
    app.efSlider3 = uieditfield(app.JointAnglePanel, '
        numeric');
    app.efSlider3.ValueChangedFcn = createCallbackFcn(app,
        @efSlider3ValueChanged, true);
    app.efSlider3.Position = [225 186 43 22];

    % Create efSlider4
    app.efSlider4 = uieditfield(app.JointAnglePanel, '
        numeric');
    app.efSlider4.ValueChangedFcn = createCallbackFcn(app,
        @efSlider4ValueChanged, true);
    app.efSlider4.Position = [225 145 43 22];

    % Create efSlider5
    app.efSlider5 = uieditfield(app.JointAnglePanel, '
        numeric');
    app.efSlider5.ValueChangedFcn = createCallbackFcn(app,
        @efSlider5ValueChanged, true);
    app.efSlider5.Position = [225 104 43 22];

    % Create efSlider6
    app.efSlider6 = uieditfield(app.JointAnglePanel, '
        numeric');
    app.efSlider6.ValueChangedFcn = createCallbackFcn(app,
        @efSlider6ValueChanged, true);
    app.efSlider6.Position = [225 63 43 22];

    % Create efSlider7
    app.efSlider7 = uieditfield(app.JointAnglePanel, '
        numeric');
    app.efSlider7.ValueChangedFcn = createCallbackFcn(app,
```

```
            @efSlider7ValueChanged, true);
        app.efSlider7.Position = [225 22 43 22];

        % Create TorqueNmPanel
        app.TorqueNmPanel = uipanel(app.UIFigure);
        app.TorqueNmPanel.Title = 'Torque                [Nm]';
        app.TorqueNmPanel.Position = [309 117 114 321];

        % Create Torque1EditFieldLabel
        app.Torque1EditFieldLabel = uilabel(app.TorqueNmPanel);
        app.Torque1EditFieldLabel.HorizontalAlignment = 'right'
            ;
        app.Torque1EditFieldLabel.Position = [0 274 54 15];
        app.Torque1EditFieldLabel.Text = 'Torque 1';

        % Create efT1
        app.efT1 = uieditfield(app.TorqueNmPanel, 'numeric');
        app.efT1.ValueDisplayFormat = '%.1f';
        app.efT1.Position = [69 270 38 22];

        % Create Torque2EditFieldLabel
        app.Torque2EditFieldLabel = uilabel(app.TorqueNmPanel);
        app.Torque2EditFieldLabel.HorizontalAlignment = 'right'
            ;
        app.Torque2EditFieldLabel.Position = [0 231 54 15];
        app.Torque2EditFieldLabel.Text = 'Torque 2';

        % Create efT2
        app.efT2 = uieditfield(app.TorqueNmPanel, 'numeric');
        app.efT2.ValueDisplayFormat = '%.1f';
        app.efT2.Position = [69 227 38 22];

        % Create Torque4EditFieldLabel
        app.Torque4EditFieldLabel = uilabel(app.TorqueNmPanel);
        app.Torque4EditFieldLabel.HorizontalAlignment = 'right'
            ;
        app.Torque4EditFieldLabel.Position = [0 145 54 15];
        app.Torque4EditFieldLabel.Text = 'Torque 4';

        % Create efT4
        app.efT4 = uieditfield(app.TorqueNmPanel, 'numeric');
        app.efT4.ValueDisplayFormat = '%.1f';
        app.efT4.Position = [69 141 38 22];

        % Create Torque3EditFieldLabel
```

```
    app.Torque3EditFieldLabel = uilabel(app.TorqueNmPanel);
    app.Torque3EditFieldLabel.HorizontalAlignment = 'right';
    app.Torque3EditFieldLabel.Position = [0 188 54 15];
    app.Torque3EditFieldLabel.Text = 'Torque 3';

    % Create efT3
    app.efT3 = uieditfield(app.TorqueNmPanel, 'numeric');
    app.efT3.ValueDisplayFormat = '%.1f';
    app.efT3.Position = [69 184 38 22];

    % Create Torque5EditFieldLabel
    app.Torque5EditFieldLabel = uilabel(app.TorqueNmPanel);
    app.Torque5EditFieldLabel.HorizontalAlignment = 'right';
    app.Torque5EditFieldLabel.Position = [0 102 54 15];
    app.Torque5EditFieldLabel.Text = 'Torque 5';

    % Create efT5
    app.efT5 = uieditfield(app.TorqueNmPanel, 'numeric');
    app.efT5.ValueDisplayFormat = '%.1f';
    app.efT5.Position = [69 98 38 22];

    % Create Torque6EditFieldLabel
    app.Torque6EditFieldLabel = uilabel(app.TorqueNmPanel);
    app.Torque6EditFieldLabel.HorizontalAlignment = 'right';
    app.Torque6EditFieldLabel.Position = [0 59 54 15];
    app.Torque6EditFieldLabel.Text = 'Torque 6';

    % Create efT6
    app.efT6 = uieditfield(app.TorqueNmPanel, 'numeric');
    app.efT6.ValueDisplayFormat = '%.1f';
    app.efT6.Position = [69 55 38 22];

    % Create Torque7EditFieldLabel
    app.Torque7EditFieldLabel = uilabel(app.TorqueNmPanel);
    app.Torque7EditFieldLabel.HorizontalAlignment = 'right';
    app.Torque7EditFieldLabel.Position = [0 16 54 15];
    app.Torque7EditFieldLabel.Text = 'Torque 7';

    % Create efT7
    app.efT7 = uieditfield(app.TorqueNmPanel, 'numeric');
    app.efT7.ValueDisplayFormat = '%.1f';
```

```
    app.efT7.Position = [69 12 38 22];

    % Create ForceNNmPanel
    app.ForceNNmPanel = uipanel(app.UIFigure);
    app.ForceNNmPanel.Title = 'Force           [N]
                              [Nm]';
    app.ForceNNmPanel.Position = [162 449 261 123];

    % Create FxEditFieldLabel
    app.FxEditFieldLabel = uilabel(app.ForceNNmPanel);
    app.FxEditFieldLabel.HorizontalAlignment = 'right';
    app.FxEditFieldLabel.Position = [-8 78 25 15];
    app.FxEditFieldLabel.Text = 'Fx';

    % Create efForceX
    app.efForceX = uieditfield(app.ForceNNmPanel, 'numeric'
        );
    app.efForceX.ValueChangedFcn = createCallbackFcn(app,
        @efForceXValueChanged, true);
    app.efForceX.ValueDisplayFormat = '%.1f';
    app.efForceX.Position = [32 74 43 22];

    % Create FyEditFieldLabel
    app.FyEditFieldLabel = uilabel(app.ForceNNmPanel);
    app.FyEditFieldLabel.HorizontalAlignment = 'right';
    app.FyEditFieldLabel.Position = [-8 46 25 15];
    app.FyEditFieldLabel.Text = 'Fy';

    % Create efForceY
    app.efForceY = uieditfield(app.ForceNNmPanel, 'numeric'
        );
    app.efForceY.ValueChangedFcn = createCallbackFcn(app,
        @efForceYValueChanged, true);
    app.efForceY.ValueDisplayFormat = '%.1f';
    app.efForceY.Position = [32 42 43 22];

    % Create FzEditFieldLabel
    app.FzEditFieldLabel = uilabel(app.ForceNNmPanel);
    app.FzEditFieldLabel.HorizontalAlignment = 'right';
    app.FzEditFieldLabel.Position = [-8 14 25 15];
    app.FzEditFieldLabel.Text = 'Fz';

    % Create efForceZ
    app.efForceZ = uieditfield(app.ForceNNmPanel, 'numeric'
        );
```

```
        app.efForceZ.ValueChangedFcn = createCallbackFcn(app,
            @efForceZValueChanged, true);
        app.efForceZ.ValueDisplayFormat = '%.1f';
        app.efForceZ.Position = [32 10 43 22];

        % Create MxEditFieldLabel
        app.MxEditFieldLabel = uilabel(app.ForceNNmPanel);
        app.MxEditFieldLabel.HorizontalAlignment = 'right';
        app.MxEditFieldLabel.Position = [90 78 25 15];
        app.MxEditFieldLabel.Text = 'Mx';

        % Create efMomentX
        app.efMomentX = uieditfield(app.ForceNNmPanel, 'numeric
            ');
        app.efMomentX.ValueChangedFcn = createCallbackFcn(app,
            @efMomentXValueChanged, true);
        app.efMomentX.ValueDisplayFormat = '%.1f';
        app.efMomentX.Position = [130 74 43 22];

        % Create MyEditFieldLabel
        app.MyEditFieldLabel = uilabel(app.ForceNNmPanel);
        app.MyEditFieldLabel.HorizontalAlignment = 'right';
        app.MyEditFieldLabel.Position = [91 47 25 15];
        app.MyEditFieldLabel.Text = 'My';

        % Create efMomentY
        app.efMomentY = uieditfield(app.ForceNNmPanel, 'numeric
            ');
        app.efMomentY.ValueChangedFcn = createCallbackFcn(app,
            @efMomentYValueChanged, true);
        app.efMomentY.ValueDisplayFormat = '%.1f';
        app.efMomentY.Position = [131 43 43 22];

        % Create MzEditFieldLabel
        app.MzEditFieldLabel = uilabel(app.ForceNNmPanel);
        app.MzEditFieldLabel.HorizontalAlignment = 'right';
        app.MzEditFieldLabel.Position = [90 14 25 15];
        app.MzEditFieldLabel.Text = 'Mz';

        % Create efMomentZ
        app.efMomentZ = uieditfield(app.ForceNNmPanel, 'numeric
            ');
        app.efMomentZ.ValueChangedFcn = createCallbackFcn(app,
            @efMomentZValueChanged, true);
        app.efMomentZ.ValueDisplayFormat = '%.1f';
```

```
app.efMomentZ.Position = [130 10 43 22];

% Create cbApplyForce
app.cbApplyForce = uicheckbox(app.ForceNNmPanel);
app.cbApplyForce.ValueChangedFcn = createCallbackFcn(
    app, @cbApplyForceValueChanged, true);
app.cbApplyForce.Text = 'Apply';
app.cbApplyForce.Position = [189 13 53 15];

% Create axesPlot14
app.axesPlot14 = uiaxes(app.UIFigure);
title(app.axesPlot14, 'Torque for joints 1-4');
xlabel(app.axesPlot14, 'Steps');
ylabel(app.axesPlot14, 'Torque [Nm]');
app.axesPlot14.Box = 'on';
app.axesPlot14.XGrid = 'on';
app.axesPlot14.YGrid = 'on';
app.axesPlot14.Position = [441 301 480 276];

% Create Animationsofmainmotionswithload4kgPanel
app.Animationsofmainmotionswithload4kgPanel = uipanel(
    app.UIFigure);
app.Animationsofmainmotionswithload4kgPanel.Title = '
    Animations of main motions with load 4kg';
app.Animationsofmainmotionswithload4kgPanel.Position =
    [21 18 402 89];

% Create btnAroundFY
app.btnAroundFY = uibutton(app.
    Animationsofmainmotionswithload4kgPanel, 'push');
app.btnAroundFY.ButtonPushedFcn = createCallbackFcn(app
    , @btnAroundFYButtonPushed, true);
app.btnAroundFY.Position = [3 41 130 22];
app.btnAroundFY.Text = 'Forward bending';

% Create btnAroundBY
app.btnAroundBY = uibutton(app.
    Animationsofmainmotionswithload4kgPanel, 'push');
app.btnAroundBY.ButtonPushedFcn = createCallbackFcn(app
    , @btnAroundBYButtonPushed, true);
app.btnAroundBY.Position = [3 10 128 22];
app.btnAroundBY.Text = 'Backward bending';

% Create btnAroundRZ
app.btnAroundRZ = uibutton(app.
```

```
        Animationsofmainmotionswithload4kgPanel, 'push');
        app.btnAroundRZ.ButtonPushedFcn = createCallbackFcn(app, @btnAroundRZButtonPushed, true);
        app.btnAroundRZ.Position = [139 41 128 22];
        app.btnAroundRZ.Text = 'Rotation right';

        % Create btnAroundLZ
        app.btnAroundLZ = uibutton(app.Animationsofmainmotionswithload4kgPanel, 'push');
        app.btnAroundLZ.ButtonPushedFcn = createCallbackFcn(app, @btnAroundLZButtonPushed, true);
        app.btnAroundLZ.Position = [139 10 128 22];
        app.btnAroundLZ.Text = 'Rotation left';

        % Create btnAroundRX
        app.btnAroundRX = uibutton(app.Animationsofmainmotionswithload4kgPanel, 'push');
        app.btnAroundRX.ButtonPushedFcn = createCallbackFcn(app, @btnAroundRXButtonPushed, true);
        app.btnAroundRX.Position = [272 41 128 22];
        app.btnAroundRX.Text = 'Sideways right';

        % Create btnAroundLX
        app.btnAroundLX = uibutton(app.Animationsofmainmotionswithload4kgPanel, 'push');
        app.btnAroundLX.ButtonPushedFcn = createCallbackFcn(app, @btnAroundLXButtonPushed, true);
        app.btnAroundLX.Position = [271 10 128 22];
        app.btnAroundLX.Text = 'Sideways left';

        % Create axesPlot57
        app.axesPlot57 = uiaxes(app.UIFigure);
        title(app.axesPlot57, 'Torque for joints 5-7');
        xlabel(app.axesPlot57, 'Steps');
        ylabel(app.axesPlot57, 'Torque [Nm]');
        app.axesPlot57.Box = 'on';
        app.axesPlot57.XGrid = 'on';
        app.axesPlot57.YGrid = 'on';
        app.axesPlot57.Position = [441 18 480 284];
end
end

methods (Access = public)

% Construct app
```

```
function app = AppDesignerRobot()

    % Create and configure components
    createComponents(app)

    % Register the app with App Designer
    registerApp(app, app.UIFigure)

    % Execute the startup function
    runStartupFcn(app, @startupFcn)

    if nargout == 0
        clear app
    end
end

% Code that executes before app deletion
function delete(app)

    % Delete UIFigure when app is deleted
    delete(app.UIFigure)
end
end
end
```

[2] Function for calculating inertia matrix

```
function [IG] = Imatrix(m,x,y,z,type)
IG = zeros(3,3);
    if strcmp(type, 'rectangle')
        IG(1,1) = 1/12 * m * (y^2 + z^2);
        IG(2,2) = 1/12 * m * (x^2 + z^2);
        IG(3,3) = 1/12 * m * (x^2 + y^2);
    elseif strcmp(type, 'cylinder')
        r = x/2;
        IG(1,1) = 1/12*m*(3*r^2 + z^2);
        IG(2,2) = 1/12*m*(3*r^2 + z^2);
        IG(3,3) = 1/2*m*r^2;
    else
        disp('Type invalid')
    end
end
```

[3] Script for calculating forces and trajectory for forward bending.

```
clear all
close all
```

```
deg = pi/180;

%Model of robot is created

%DH-parameters
L(1) = Revolute('a',0,      'd', 0.333, 'alpha',-pi/2);
L(2) = Revolute('a',0,      'd', 0,     'alpha',pi/2);
L(3) = Revolute('a',0.088,  'd', 0.316, 'alpha',pi/2);
L(4) = Revolute('a',-0.088,'d', 0,     'alpha',-pi/2);
L(5) = Revolute('a',0,      'd', 0.384, 'alpha',pi/2);
L(6) = Revolute('a',0.088,  'd', 0,     'alpha',pi/2);
L(7) = Revolute('a',0,      'd', 0.107, 'alpha',0);

%joint angle limits
L(1).qlim = [-170 170]*deg;
L(2).qlim = [-150 150]*deg;
L(3).qlim = [-170 170]*deg;
L(4).qlim = [-180 5]*deg;
L(5).qlim = [-170 170]*deg;
L(6).qlim = [-5 220]*deg;
L(7).qlim = [-170 170]*deg;
L(8).qlim = [-180 180]*deg;

%inertia matrix
L(1).I = (Imatrix(1,0.1,0.2,0.140,'rectangle'));
L(2).I = (Imatrix(1,0.133,0.113,0.193,'cylinder'));
L(3).I = (Imatrix(1,0.133,0.133,0.303,'cylinder'));
L(4).I = (Imatrix(1,0.11,0.11,0.210,'cylinder'));
L(5).I = (Imatrix(1,0.1,0.1,0.35,'cylinder'));
L(6).I = (Imatrix(1,0.095,0.095,0.18,'cylinder'));
L(7).I = (Imatrix(1,0.088,0.088,0.136,'cylinder'));
L(8).I = (Imatrix(1,0.088,0.088,0.054,'cylinder'));

%mass
L(1).m = (3);
L(2).m = (3);
L(3).m = (3);
L(4).m = (3);
L(5).m = (2);
L(6).m = (2);
L(7).m = (2);
L(8).m = (2);

%position of center of mass relativ to reference frame in each link
```

```
L(1).r = ([0,0,0.14/2]);
L(2).r = ([0,0.193/2,0]);
L(3).r = ([0,0,0.303/2]);
L(4).r = ([0,0,0]);
L(5).r = ([0,0,0.35/2]);
L(6).r = ([0,0,0]);
L(7).r = ([0,0,0]);
L(8).r = ([0,0,-0.054/2]);

 robot = SerialLink(L, 'name', 'Panda');

%New and old start pose for robot.
%Both assumed task space and joint space vector

%New start position
% T_start_assumed = [1 0 0 0.725;
%               0 -1 0 0;
%               0 0 -1 0.44;
%               0 0 0 1];
% q_start_assumed = [0 31 0 -73 0 105 0 0]*(pi/180);

%Old start position
%assumed initial task space
 T_start_assumed = [1 0 0 0.419;
                    0 -1 0 0;
                    0 0 -1 0.37;
                    0 0 0 1];
%assumed initial joint space
 q_start_assumed = [0 -18 0 -148 0 127 0 0]*(pi/180);
 load_patient = 40;

%initial position is calculated
 q_start_calc = robot.ikcon(T_start_assumed, q_start_assumed); %initial joint space
 T_start_calc = robot.fkine(q_start_calc); %initial task space
 T_start_calc = T_start_calc.T;
 start_xyz = T_start_calc(1:3,4)';
 load('rotation_f_y.mat'); %data points from Tracker
X = rotation_f_y(:,1)';
Z = rotation_f_y(:,3)';

%data points from Tracker are fitted to the reference frame
 diff_x = start_xyz(1) - X(1);
X = X + diff_x;
```

```
diff_z = start_xyz(3) - Z(1);
Z = Z + diff_z;
figure(1)
plot(X,Z,'Linewidth',3);

N = length(X);
Q = zeros(N, 8);
QD = zeros(N,8);
QDD = zeros(N,8);
Q(1,:) = q_start_calc;
torque = zeros(N,8);
theta = linspace(0,-70*deg,N);
trajectory = zeros(N,3);
trajectory(1,:) = [X(1) 0 Z(1)];

%joint anglees and forces are calculated for each step
for n = 2:N
    q_previous = Q(n-1,:); %previous joint angles

    %assumed orientation
    T_assumed = [cos(theta(n)) 0 sin(theta(n)) 0;
        0 -1 0 0;
        sin(theta(n)) 0 -cos(theta(n)) 0;
        0 0 0 1];

    %assumed position from Tracker
    T_assumed(1:3,4) = [X(n) 0 Z(n)];

    %inverse kinematics to find joint space
    Q(n,:) = robot.ikcon(T_assumed, q_previous);
    T_calc = robot.fkine(Q(n,:));
    T_calc = T_calc.T;
    trajectory(n,:) = T_calc(1:3,4)';
    %inverse dynamics to find forces in each joint
    torque(n,:) = robot.rne(Q(n,:), QD(n,:), QDD(n,:), '
        fext', load_patient*[cos(theta(n)) 0 sin(theta(n)) 0
         0 0]);
end

%plot animation
figure(2)
robot.plot(Q(1,:));
robot.animate(Q);

%plot
```

```
figure(1) %Points from Tracker vs. calculated slope
hold on
title('Forward rotation around y-axis')
plot(trajectory(:,1), trajectory(:,3),'.','MarkerSize',25);
legend({'Trajectory from Tracker', 'Trajectory of Robot'},'Location','southeast');
xlabel('x-axis [m]')
ylabel('z-axis [m]')

save('trajectory_f_y.mat','trajectory')
save('Q_f_y.mat','Q')
save('torque_f_y.mat','torque')

figure %torque in joint 1-4
plot(torque(:,1:4),'Linewidth',3)
title('Torque for joint 1-4[Nm]')
legend('Joint 1', 'Joint 2', 'Joint 3', 'Joint 4', 'Location', 'eastoutside');
hold on
plot([0 N], [87 87], 'black','Linewidth',3)
plot([0 N], [-87 -87], 'black','Linewidth',3)
grid on
xlabel('Step')
ylabel('Torque [Nm]')

figure %torque in joint 5-7
plot(torque(:,5:7),'Linewidth',3)
title('Torque for joint 5-7[Nm]')
legend('Joint 5', 'Joint 6', 'Joint 7', 'Location', 'eastoutside');
hold on
plot([0 N], [12 12], 'black','Linewidth',3)
plot([0 N], [-12 -12], 'black', 'Linewidth',3)
grid on
xlabel('Step')
ylabel('Torque [Nm]')
```

Appendix H

Specialization project

Specialization Project

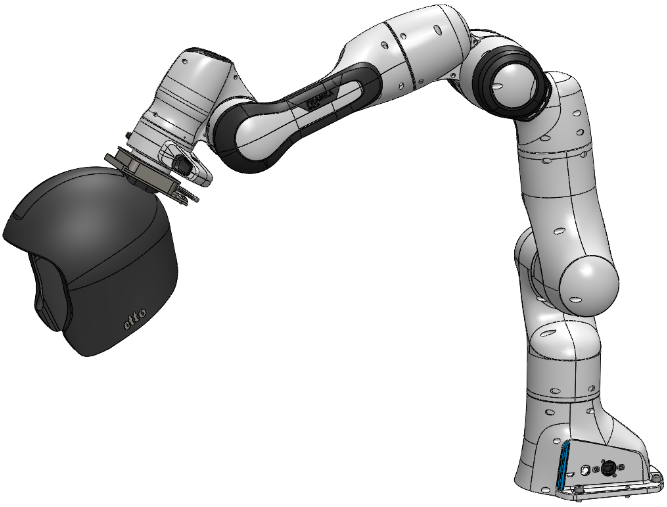
NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Mechanical and Industrial Engineering

Stian Krogstad Brattgjerd

Development of a new machine for rehabilitation of whiplash patients

TMM4560 – Engineering Design and Materials, Specialization Project

Trondheim, December 2017



NTNU
Norwegian University of
Science and Technology

I would like to especially thank my supervisor Knut Einar Aasland for assisting me during the specialization project, and organizing a trip to Munich. I would also like to thank Morten Leirgul at Firda Physical-Medical Center for welcoming me to Sandane, giving me a decent walk through at Firda, and being available for questions during the project time. Lastly i would like to thank assistant supervisor Kristoffer B. Slåttsveen and my friends Caroline Marie Minsaas and Emil Scott Bale for proofreading the project report and giving highly valued feedback, and a special thanks to my father, Svein Birger Krogstad for guiding me through workshop activities.

NTNU

Development of a new machine for rehabilitation of whiplash patients

Specialization project autumn 2017

The specialization in the 9th semester consists of a specialization project and a corresponding specialization course. The specialization project works as a preliminary study ahead of the master thesis, and is mandatory for students at the Department of Mechanical and Industrial Engineering(MTP). It serves to give the student insight and a taste of the upcoming last semester consisting of solely the master thesis.

This is the 4th specialization project that is conducted on the matter, and serves as a collaboration between MTP and Firda Physical-Medical Center in Sandane. The project involves experimental work which has been evaluated through a risk assessment found in the appendix.

The deadline for the project is 13th of December, and two copies is to be delivered each, in paper- and electronic format to the administration at MTP.

Author: Stian Krogstad Brattgjerd
Delivered: December 2017
Supervisor: Knut Einar Aasland

Norwegian University of Science and Technology
Department of Mechanical and Industrial Engineering

Summary

This is a specialization project conducted the autumn of 2017 by Stian Krogstad Brattgjerd. The project is about development of a new machine for rehabilitation of whiplash patients, and has been ongoing since the fall of 2014. A total number of 4 master thesis and 3 specialization projects has been conducted on the matter. The project is a collaboration between NTNU and Firda Physical-Medical Center(FPMC).

Today FPMC conducts part of their rehabilitation training through a machine called the Multi-Cervical Unit(MCU). The patient sits inside the machine, and straps his/her head in a head mount. The machine works like an ordinary training apparatus where weights and gravity produce force against the patients movements. FPMC is not pleased with the current MCU. It is old fashioned, and the producer has no plan of further development on its design. As a result, a partnership between FPMC and NTNU was establish, with the intent of making a new machine.

Since the start, numerous designs and prototypes has been developed, but today the design consists of a robotic arm, which will serve as the motion platform for the machine. The first part of this specialization project involves an assessment of the previous work and research of relevant literature.

The second part utilizes different product development methodologies to design a head mount to connect the patients head to he robot arm, and an accompanying mounting mechanism between them. The head mount consists of an alpine helmet with an inflatable padding to provide an even pressure against the patients head. The mounting mechanism is made in stainless steel, and uses a window latch to lock the helmet together with the robot arm.

Before a finished working prototype of the machine can be tested, some components must be further developed. The head mount needs further development and testing. A seat for the patient based on earlier studies will be built along with a sturdy framework surrounding the robot arm and the rest of the components. This work will be continued in the master thesis.

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Abbreviations

MCU = Multi-Cervical Unit
FPMC = Firda Physical-Medical Center
CAD = Computer Aided Design
DoF = Degrees of Freedom
PD = Product Development
MTP = Department of Mechanical and Industrial Engineering
PLA = Polylactic acid

Chapter 1

Introduction

This specialization project aims to continue the work that has been done on the development of a machine for rehabilitation of whiplash patients. The project will serve as a preliminary study ahead of the mater thesis which will be conducted during the spring of 2018.

1.1 Background

It is estimated that around 26 000 Norwegians suffer from neck related injuries each year. The most common form of injury, is whiplash due to high momentum accidents. The type of accidents varies, but the most frequent ones are car crashes or sport injuries. The extend of damage varies from mild and moderate cases, where simple over the counter drugs and self healing will suffice, to more severe cases where regularly recovery training and follow-ups are needed. In the few worst case scenarios, medical surgery must be performed. The Norwegian association of neck trauma has estimated that as much as 400 people becomes completely occupationally disabled each year. In addition, as many as 1 350 people gets partially disabled. The most common symptoms of the neck trauma is headache, reduced neck movement, along with pain, dizziness and nausea [10].

Sandane, in Norway, has one of the few facilities that specializes on whiplash injuries in all of Scandinavia, and in 2014 a partnership between Firda Physical Medical centre(FPMC) and NTNU, Department of Mechanical and Industrial Engineering(MTP) was established. FPMC beleives that one of the solutions to treating moderate to severe whiplash cases, is by doing recovery training of the muscles around the damaged area. In this regard, FPMC has used a machine called the MCU, or the Multi-Cerical Unit. This machine isolates the appropriate muscles in the neck in order to focus the recovery training to the damaged area. The machine, along with the professional help and guidance of the employees at FPMC, has a very good track-record, and as many as 215 out of 222 people has given feedback that their treatment at Firda has improved their situation[11].

There is however room for improvement with regards to the MCU. The machine is old fashioned, poorly adjustable and does not permit an appropriate user interface for an optimized treatment. It has been conducted three specialization projects and four master thesis on the development of a new machine. The first thesis written by Kristoffer Bjørnerud Slåttsveen and Sondre Frantsen Tolo, investigated the use of a Stewart platform and showed a lot of potential with regards to free movement preferred by FPMC. The work was continued by Ole Jacob Berg and Østein Kavle Sunde, but the solution displayed limitations with regards to large angular displacements. The latter, developed a new platform they called Masnak. Unfortunately, their solution did not permit free movement as favored by FPMC.

The most recent thesis written by Thomas Erik Lyngman Gælok and Michelle Strand aimed to develop the smaller components of the machine along with investigations on a cable robot as the movement platform. They came up with promising concepts regarding fixing the head of the patient to the machine, and the development of a software interface to use with the machine. Their research also concluded on a robot arm as the best solution for the platform.

1.2 Agenda

The intention of this specialization project is to continue where Gælok and Strand left off, and keep on working on the development of the new machine. This specialization project is focusing on three aspects of the development of the machine. It concludes with using a robot arm as the movement platform, further investigates a head mount for the patient, and fully develops a mounting mechanism between the motion platform and the head mount.

The next chapter will summarize the most important discoveries since the start of the project. Thereafter some basic theory needed for understanding the main concepts and decision making. Chapter 4 explains the methods used to develop the different concepts, followed by the product requirements in chapter 5. Concepts will be revealed in chapter 6, and the two last chapters evaluates the specialization project and states the future work.

Chapter 2

Previous work

The development of a new machine for rehabilitation of whiplash patients is a project that has been going on since 2014. Up until now, four master thesis and three specialization projects have been conducted on the subject. The work has mainly been feasibility studies on mainly three topics

- **Motion platform**
  The component of the machine that will provide resistance against the patients movement.
- **Head mount**
  A mechanism that connects the patients head to the machine.
- **Seat**
  Suitable seat with the patients comfort and fit in mind.

In each case there have been several concepts up for evaluation, and they will be further investigated in the following sections.

2.1 Motion platform

2.1.1 Multi-Cervical Unit

As explained earlier, the procedure of rehabilitation of whiplash patients is mainly conducted through the MCU. The MCU is built by an American company named BTE tech, and is essentially the main distributor of such apparatus in the world[1]. The machine has not been noteworthy developed since its release back in the end of 1990, and they have no plan to develop it further.

What is most astonishing when considering that the MCU is a medical device, is its simplicity. It works almost like any other training apparatus, except with a few adjustments. It is a weight based resistance system, and the only thing the patient do, is placing his/hers head in the head mount, and moves the head forwards and backwards in a circular path around one axis(y). The machine can be adjusted to train sideways motion, also in a circular path around one axis(x). Simple rotation of the head can also be conducted. This really restricts the area of which the patient can move, as combinations of the three latter motions are impossible.

Figure 2.1: Multi-Cervical unit [1]

2.1.2 Stewart platform

The first concepts of the machine was developed by Kristoffer Bjørnerud Slåttsveen and Sondre Frantsen Tolo, and involved a Stewart platform[12]. This is a parallel connection robot manipulator, which means its links and joints create anything from two, or more serially connected chains. These chains are the connection between the base and end effector of the robot (see figure 2.2).

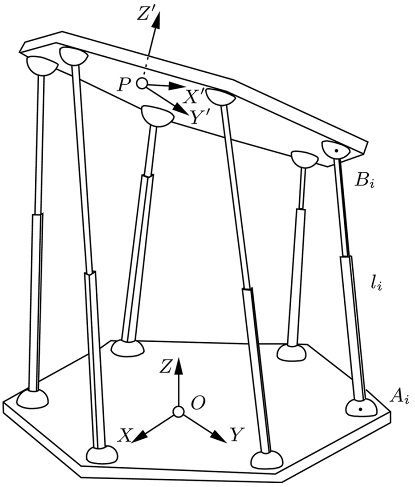

Figure 2.2: Stewart platform[2]

The design makes the platform very powerful, and it is used in everything from flight simulators, heavy lifting and directional adjustment of huge telescopes[13]. When Slåttsveen and Tolo investigated this mechanism, it came forth that the platform had already been used in rehabilitation training of ankle joints[14], which gave great expectations.

The Platform gives the patient good mobility in all directions, including a combination of movements. The platform also enables the patient to follow his own axis of movement, and not around axes of the machine as in the MCU. FPMC wanted to use the new machine for research together with their treatment, something of which the Stewart platform with its electrical actuators and programming would be well suited for.

In 2015 Ole Jacob Berg and Østein Kavle Sunde continued the project, and did several analysis both physical and numerical, to comprehend the potential of the platform. They uncovered that the preferred angular displacement given by FPMC was impossible to impose with the platform at certain movements. A collapse due to singularities (see subsection 3.3.1) was identified around 30 degrees, which was only half of the required displacement of 60 degrees(see appendix **??**). Additionally there were uncertainties regarding licensing for robotic devices applied in medicine. This ended in discarding of the Stewart platform, and the development of a new platform called MASNAK.

2.1.3 MASNAK

MASNAK is a new form of robot concept developed in the Berg and Sunde thesis[3]. It is a linear actuator controlled multi-joint mechanism. It consists of two serially connected five-joint mechanisms, and allows for free movement in one plane. The platform uses four linear actuators which will act passively against the movement of the patient. To change between sideways to back and forth the patient must be rotated 90 degrees. This solution gave no singularities and no restrictions with regards to angular displacement. The problem with this solution was that motions were locked to one plane, and the amount of exercises would thereby be limited. In their project and master thesis, Thomas L. Gælok and Michelle Strand was supposed to develop this platform further, but due to the limitations of movement, chose to have a closer look at the possibilities of using a cable robot[4].

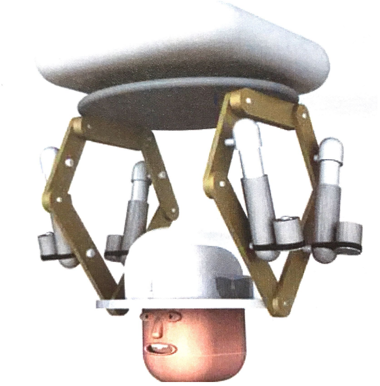

Figure 2.3: MASNAK platform[3]

2.1.4 Cable robot

Gælok and Strand developed a CAD of a cable robot shown in figure 2.4. The head of the patient would be in the center of a cube, connected to cables which goes to each respective corner of the cube. The idea is that each cable goes through pulleys and then to a winch. The winches will be connected to a control unit, which will handle the different cable lengths and give appropriate resistance to the patient.

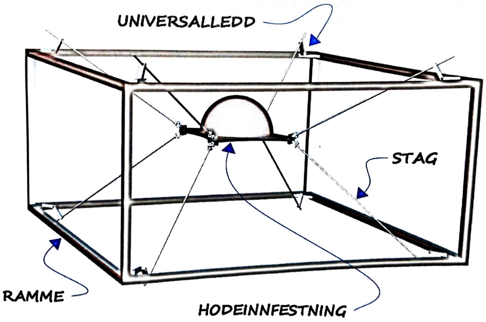

Figure 2.4: Cable robot platform[4]

A safety concern was raised regarding the strength of the machine. A solution was a 50N magnet in each cable, which would break under a higher force. They also had frequent contact with an experienced professor at Fraunhofer Institute for Manufacturing Engineering and Automation, in Germany. He and his team had been working on a cable robot a couple of years, and stated that getting accurate positioning with the winches is very hard. They had used over 18 months to develop the winch used in their project. He also stated that the price of one of their winces would be around 10 000 Euros, and Gælok and Strand needed 8 winches to avoid singularities in their design. The conclusion due to the complexities of the cable robot, no one on the team with knowledge in the field, and uncertainties regarding medical certifications, the cable robot was disregarded. Now all that was left was considering a robot arm as the platform.

2.1.5 Robot arm

During Gælok and Strands work[4], a new type of robot arm was introduced to the market. The Panda robot developed by Franka Emika, is the only robot in its field with a substantial and sophisticated feedback system provided by torque sensors. This opened the possibility of using a robot arm as the platform. The concept involves the patient being connected to the end effector of the robot arm. The robot arm will then act passively against the patients movement when the sensors feel the patient move.

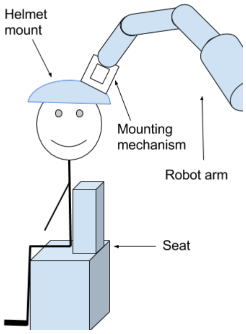

Figure 2.5: Robot arm concept[Author]

The force of the arm can be adjusted depending on the severity of the patients injury. Virtual walls can be created in the software, thus blocking and thereby guiding the correct motion of the head. This makes setting up rehabilitation programs for the therapist much easier. The price of the robot is roughly 10 000 Euros, and it has 7 degrees of freedom, thus reducing problems regarding singularities (see subsection 3.3.1). The biggest problem was establishing how much resistance the robot could deliver. A physical test was conducted during a company visit at the start of the specialization project. The results were good, and the Panda robot arm was thereby chosen as the motion platform.

2.2 Head mount

Through Gælok and Strands specialization project and master thesis a total of 10 concepts has been developed. Each concept was investigated with regards comfort, slack, size range, easy to attach, weight ect. There is of little use to explain every single design in detail, but the two most promising designs will be looked at further.

2.2.1 Padded head mount

Using pads to symmetrically press against the head was a promising solution. The pads tested in different material, would be pressed against appropriate areas of the head to make a rigid connection. Gælok and Strand made a test rig, and tested out different types of padding to mainly investigate its comfort, slack and adaptability to different head sizes. Air-pillows, cellular rubber, gel, polyfoam and plastelina was tested. All in all the best result was from the plastelina padding. It gave little slack, was comfortable, and felt good when moving the head in the different directions. For a final solution the design has to be further developed. The amount of pads, shapes and the mechanism of how to press it against the head must be investigated. The design also has to provide a good solution with regards to a symmetrical mounting of the head, so that it is placed completely in the center of the mount.

2.2.2 Inflatable head mount

This concept involves using a helmet. The helmet will provide the mount with a rigid and hard shell. On the inside of the helmet, inflatable elements are placed. When the patient fits his or hers head inside the helmet, the elements are inflated, thus creating an even force around the patients head. This solution will also fit several different head sizes, as a bigger head would only result in less inflation, compared to a smaller head. Gælok and Strand investigated the use of one single inflatable element, and several, but smaller elements. The conclusion leaned towards one element being the best alternative. The prototype was made of an inner tube surrounded by a simple hardhat. Aside from the design being very simple, it was perceived as very comfortable. There was however some slack when doing the different head movements, but was assumed to become better in a more sophisticated prototype. The model must be further developed to be usable in the machine. Optimal placement of the inflatable elements must be considered, and a suitable way of inflating should also be looked at.

2.3 Seat

In 2015, Marius Kirkeeide wrote his thesis investigating what type of chair module to implement in the machine[5]. His work resulted in two different chair concepts. The first one is a seat-based system, and the second one is a more modular system open for modifications.

2.3.1 Seat based design

The seat based design resembles a simple chair, but differs with the fact that it is highly adjustable to fit the different body shapes and lengths. Height is adjusted by two electrical linear actuators which is controlled by either the patient or physiotherapist. It has adjustable armrests with side supports against the thigh. The back support is provided by three independent pads, that is controlled by linear actuators, and can move up or down, in or out. This solution provides very good adaptability to most body types. The actuators positions can be stored in a computer system, and the patient will get his/hers adjustment settings with a push of a button. The solution is however quite sophisticated, and will require at least five linear actuators along with a control unit to cope with the suggested adjustments.

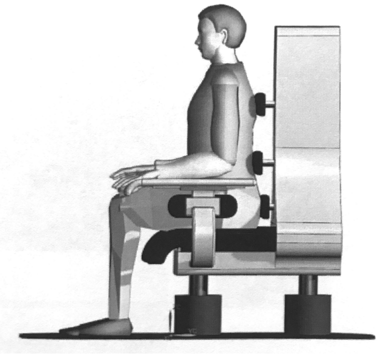

Figure 2.6: Seat based design[5]

2.3.2 Module based design

As the title suggests, this design is more based on a general platform that can be modified by adding or removing parts easily. Another difference, is that the solution offers the patient an opportunity to stand while exercising. This provides the therapist with more options when it comes to setting up a more advanced recovery training program. The deign consists of two vertical columns that form a rail system. In the rail system, different modules can be attached. In the bottom there is a foldable chair, and when upright gives the patient the ability to stand. The design has back, side and arm supports as the seat based design. Due to the folded seat, the modular design is not as adjustable to all body shapes and lengths. When standing, the folded seat will for instance prevent the three back support pads to reach people below an average height. On the upside, this solution is not as complicated, and easier to manufacture and assemble.

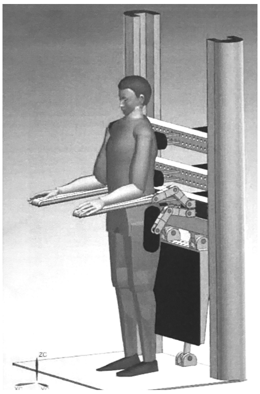

Figure 2.7: Module based design[5]

2.4 Summary

After reviewing the work that has been done on the development of a new machine for rehabilitation of whiplash patients, it has become clear that a big chunk of the job is already done. Several of the designs can be fully implemented in the final design, whilst some will need adjustments and re-designs. Since a final decision on the motion platform has been made, there are mainly four components to be looked into and developed before we have fully functional prototype. First we need to settle on a final **head mount design**. Secondly a **mounting mechanism** between the head mount and the motion platform. Lastly, the **framework** for the entire machine and a suitable **chair** has to be designed. The next two chapter reviews the different theories and design methods implemented in the specialization project.

Chapter 3

Theory

When designing an apparatus designed for recovery training of whiplash patients, some knowledge about the neck is mandatory. The basic structure and certain parts of the anatomy is looked into. There will also be a short introduction to robotics and the robot arm.

3.1 Anatomy of the neck

The neck is one of the most complex parts of the human body, due to its different shapes and structures located around a small area. This area is also one of the most vulnerable, as it contains several vital organs including big blood vessels, nerves and the spinal cord[15]. The purpose of the neck, is to connect the head with the torso, and additionally provide adequate mobility. The neck is located at the uppermost part of the spine, and accounts to seven of a total number of 33 vertebrae along the length of the spine. The necks structure gives the head a range of approximately 6-degrees of freedom[16], and the pattern of movement is usually rotation, flexion and extension. The necks vertebrae is called(counting from top to bottom), C1, C2, C3 and so on(see figure 3.1).

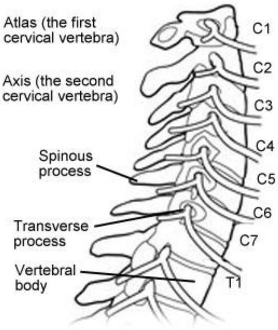

Figure 3.1: Cervical spine anatomy[6]

Vertebral C1 and C2 is called atlas and axis. They stick out from the rest, as they provide a much greater deal of mobility. C1 acts like a ring/washer that the skull rests upon, thus providing most of the rotational movement of the cervical. Due to the configuration of C2, it is responsible for most of the flexion and extension of the neck[6].

3.2 Whiplash

Whiplash is a sudden acceleration and/or deceleration movement of the body, which causes the head to bounce back and forth[17]. The phenomenon occurs due to the necks inability to withstand the large forces, and can have a catastrophic outcome for the victim. The most common episodes causing whiplash is vehicle collisions and sport accidents, but lighter versions can occur in daily life activities.

The mechanism of a whiplash injury varies with the extent of the acceleration/deceleration. The damage is also a very disputed matter due to the complexity of the cervical. The forward and backward jerking motion could cause damage to ligaments causing them to deform plasticly, which means they will not return to their normal position and shape. In more severe cases damage to joints, cervical muscles and nerves can occur, along with completely torn ligaments(see figure 3.2).

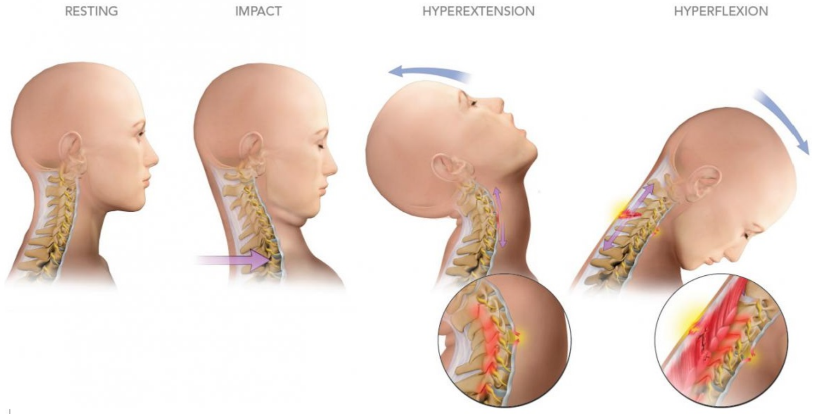

Figure 3.2: Whiplash mechanism[7]

3.2.1 Treatment

There are mainly three different types of damages when considering whiplash, and they are muscle-, nerve- and joint damage[18]. The treatment of the injuries are very dependent on the extent of damage. Light to moderate injuries can be treated by self-care advice and over the counter drugs to relieve pain[19]. More severe injuries requires more disciplined recovery training, and in special cases, medical surgery.

Firda Physical Medical Centre in Sandane, believes that when the ligament and muscles in the neck gets weakened, the neck struggles to carry the weight of the head, and the muscles around gets overworked and results in pain[18]. A solution to this problem is to do recovery training of the damaged area of the neck, and this is where the MCU, or the Multi-Cerical Unit comes in. The machine serves to provide weight-based resistance against the patients movement of the head. The resistance can be adjusted depending on the injury, and provides adequate recovery training of the damaged area. When the patients condition improves they are given an extensive recovery training program they can follow on their own time. Most of the patients experience a significant improvement after the treatment.

3.3 Robotics

The term robots has fascinated people ever since Arnold Schwarzenegger appeared as the Terminator back in the 80s. But what does the word really mean? Robotics may conjure up to various levels of technological sophistication, and ranges from simple material handling appliances in a manufacturing company to a two legged, two handed robot much like the film. Today, robotics are widely used all over the world. In almost every production company, you will find one or more industrial robots doing tasks like welding, cutting, milling ect. all in the purpose of consistency and eliminating human error.

The modern robot is an incorporation of mechanical, electrical and computer science. The types are usually divided in to the field of application, the degrees of freedom or the range of which the robot can work[20]. In the case of the specialization project, the whiplash recovery training machine will be a stationary device. This means we need a stationary robot, preferably a robot arm.

3.3.1 Robot arm

A robotic arm is a programmable, mechanical arm capable of functions very similar a human arm. It has one end effector, which is the part of the robot that interacts with the environment, and one or more stationary base(s)[21]. The most important part when finding a suitable robotic arm, is defining the degrees of freedom(DoF) needed for an optimal operation. The DoFs of an object, refers to its freedom of movement in a three-dimensional space. To establish the number of DoFs, we consider translation along the x-,y- and z-axis, and rotation perpendicular to the latter(see figure 3.3).

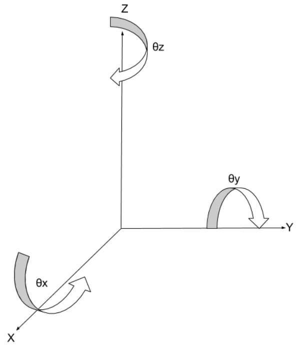

Figure 3.3: 6 Degrees of freedom[Author]

Robotic arms can have everything from one to several DoFs, and the total count are usually gathered from the number of rotational joints in the robotic arm. It is very important to consider singularities when choosing an appropriate robot. Singularities can happen when two robot axes(or more) align, which causes the robot to behave unpredictable, or not move at all. This phenomena happens when a robot arm does not have a sufficient amount of DoFs, or it is moving to an area causing singularities. As stated in 3.1 the neck has a total of 6 degrees of freedom, and the the platform used in the machine should have no less. There are also special requirements when a robot will be associating with humans [21, 22].

Chapter 4

Methods

This chapter will bring to light the different methods applied through the project. A big part of this specialization project has been to read and assess what has been done in the earlier development of the machine, and getting a decent overview of what has worked and what has not. In any case, different learning techniques was implemented along with frequent contact with both the supervisor and the client at FPMC.

As this is a product development project, different product development design methodologies will be introduced, and how they have been essential throughout the development process. The methods has been chosen carefully with regards to earlier experience, decision making and relevance. This chapter will further explain in detail, flexible product development, set-based design and prototyping.

4.1 Flexible product development

Product development(PD) is a versatile activity, and can be implemented in projects, marketing, production as well as in leadership assignments[23]. However, in this case we will have a look at product development in a more design-, function- and application point of view. developing a new product is not easy, and therefore different methodologies can be of much help reaching our goal. It is a common saying that doing a substantial amount of PD, reduces risk and helps dealing with knowledge gaps.

The standard point based development strategy is often said to put a straitjacket on innovation by deciding on the specifications of the design very early, not allowing for changes later in the process. It can also lead to late discoveries in the design, which would require a substantial amount of rework. The reason for doing point based development is that leadership usually wants heavy up-front planning to reach their goals, but this has an unfortunate effect by constraining the design and innovation process, as a result. As a push-back to this strategy, flexible product development has become growingly popular when designing a new product, and allows for much more freedom in the development process[24].

Flexible product development introduces the ability to make changes in the product later in the development process. Preston Smith stated that flexibility is the key-word in this strategy, and the later you are able to make changes in your design, the more flexible the process becomes. In addition the less disruptive the changes are, the more flexible the process is[25]. This means that when designing and developing a product such as the whiplash machine, you should leave the parts or pieces open for modification as long as possible, without disrupting other criteria of the design like for instance its function, weight or size.

One of the dangers when focusing too much on flexibility is that the design becomes too adaptable to changes, which again cause problems in decision making, and result in waste of time and money. Smith suggests that flexibility should be applied where you need to be innovative. In this project there will be room for a lot of flexibility, and a method like set-based design can greatly help figuring what should be flexible or not.

4.2 Set-based design

As suggested in the previous section, set-based design is a practice that keeps elements of the design open for adjustments and changes, whilst locking others. By doing so, the method allows the designers to explore and identify several solutions, weighing them against each other, and avoid bad choices. A final decision is made only when the solutions has been validated through proper simulations and/or simple testing[8, 25].

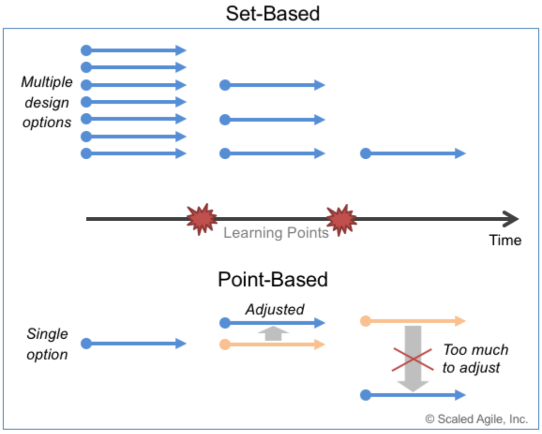

Figure 4.1: Set-based and point-based design[8]

As a summary, set-based design defines a set of solutions running parallel to each other(see figure 4.1). Each solution is explored and analyzed, gradually narrowing down the amount of solutions through so-called learning points. Each learning point is a step closer to one single solution. When the final solution is established, it is locked, meaning it does not change unless absolutely necessary. By conducting set-based design when for example determining on an optimal mounting mechanism between the robot arm and the helmet, the risk of doing rework due to a sloppy design is greatly reduced. But how can the different design solutions be validated, and should solutions be physically tested before a final decision is made?

4.3 Prototyping

Developing new products, and deciding on a suitable design can seem easy from an outsiders perspective. Even a simple ballpoint pen with its relatively universal design, has several hundred engineering hours behind it with regards to looks, function, durability, reliability and manufacturing. Good product development is all about reducing risk and knowledge gaps, and a great tool to do the latter, is prototyping.

Albert Einstein once ascertained ”*Whats the difference between theory and practice? In theory they are the same. In practice, they are not*”[26]. Prototyping is a product development process that uses a combination of methods in order to give an idea, a physical and/or visual form. The method enables the designers to specify problems in the design with focus on requirements, solutions and user needs. Implementing a prototype allows the design, product or service to ”practice being itself”, thus learning more about what has been done, and what should have been done differently. Usually we think of prototypes as a physical one-of-a kind sample model. But as a matter a fact 3D models in CAD, 3D printed objects and even simple sketches all go under the definition of a prototype[27].

How would you know that your product will work if you only have the theory to back it up? The truth is you don’t. Without a prototype, you can’t test the design before its been built. Take the Wright brothers as an example, which invented, built and flew the first successful airplane. How did a couple of bicycle repair men manage to do it when engineers and scientists failed? It all started with the building of a wind-tunnel to test different prototypes of wing profiles. Instead of testing by the second(fly and crash), they tested by the hour[28]. Incorporating the use of prototypes either early or late in product development can help minimize design errors that otherwise could occur. They are also inexpensive, and are of much help for design engineers when identifying issues both in a disciplinary and cross disciplinary field. The latter is especially applicable when doing experience prototyping [29].

4.3.1 Experience prototyping

In short Marion Buchenau and Jane Suri defined experience prototyping as a kind of representation, in any medium, that is designed to understand, explore and communicate what it might be to engage with the product, space or system that we are designing[30]. To put it simple: it is a way for the designers, clients and/or users to experience the product themselves through a prototype. Instead of passively witnessing the product through a demonstration, the audience is active in the process, and helps the designers with validation and verification with certain aspects of the product. The concept of experience prototyping is that experience is primarily subjective for each individual, and the best way of understanding experiential qualities and features is by experiencing it subjectively[31].

Chapter 5

Product requirements

Chapter 2 describes the most promising concepts developed by former students running this project. The machine as a whole consists of several parts, and looking into requirements of each specific component is superfluous, given that this is just a preliminary project ahead of the master thesis. The requirements concerning the platform used in the machine for rehabilitation of whiplash patients was thoroughly specified in the thesis by Gælok and Strand. The specifications is found in appendix **??**, and will not be investigated further in the specialization project. The requirements relevant for this project concerns the **head mount**, and a **mounting mechanism** between the head mount and the robotic arm.

5.1 Head mount

Previous designs and prototypes of the head mount is also described in chapter 2, through the earlier studies by former students. Before a final decision can be made, a more advanced prototype needs to be built and tested, as stated under *future work* in the Gælok and Strand thesis[4]. The products requirements are well formed by continues collaboration with FPMC. Each requirement is listed below with adequate details.

Universal fitting
Because of the vast difference of head shapes, the head mount should be able to fit any head shapes or forms. If the mount does not permit a decent fit, it will effect the patients sense of comfort and quality, thus having an undesirable effect on the recovery training.

Minimal play
The head mount should be as tight as possible, and allow for no or a minimal amount of play between the head and the mount. This is especially important regarding the patients motions and receiving the correct data from the robot and its torque sensors. A poorly fitted head attachment could also promote unwanted movement of the neck.

Symmetrical fixture
A symmetric fixture of the head is important for getting the head in the centre of the mount. This should be a repetitive function, meaning that the head will end up in the same place each time it is attached. If the head is not in the center of the mount it can affect the patient doing the correct movements.

Comfort
Since one session in the machine will last for about 30 minutes, it is important that the head mount does not become uncomfortable during this time. It should also allow for some venting to prevent that the patient becomes too hot and/or sweaty.

Soothing design
The design should not look scary for the patient. Preferable the design should have familiar look thus avoiding that the patient becomes tense before or during the recovery training. Additionally it should not obstruct the patients eyesight, thus minimizing a feeling of claustrophobia.

Easy to attach and detach
The process of attaching and detaching the head to the mount should go easy and simple. If the patient for some reason feels uncomfortable using the mount, he or she should be able to detach themselves from the head mount to prevent panic or anxiety when using the machine.

Lightweight
The design should be relatively light. If the design gets too heavy it might feel uncomfortable for the patient, and since the robotic arm can only produce a certain amount of resistance, a heavy head mount might come into play with regards to the robots maximum strength.

Do not obstruct movement
Because of obvious reasons, the head mount should not obstruct the patients movement of the head under the recovery training.

5.2 Mounting mechanism

The mounting mechanism is the component that connects the robotic arm with the head mount. This mechanism has not been looked into in any of the earlier projects, which makes sense since nor a platform or head mount had been chosen. The requirements of the mounting mechanism is listed below with adequate information.

No play
The mechanism that locks the head mount to the robot arm should prohibit any form of play once mounted. This is important for inducing the proper motions by the patient. A poorly designed mechanism would also effect badly on the overall sense of quality of the machine. The patient may also become insecure if he feels and/or hears that the mechanism is not sturdy and tight under use.

Easy to attach and detach
Attaching the head mount to the robot arm should be a procedure done by the physio therapist. This to ensure that the mechanism is properly attached and does not fall off or loosen during rehabilitation. The attachment and detachment should go quick and easy.

Lightweight
Once the mechanism is attached, it becomes part of the head mount, and as stated in subsection 5.1 it should not be too heavy.

Soothing design
Similar to the head mount, the mounting mechanism is something that is visible to the patient, and should not have a scary look. Preferably have a familiar design, and a mechanism recognized from everyday life.

Simple manufacturable design
Since a mounting mechanism can quickly become extremely complex with lots of geometry and uneven symmetry, it should be designed as easy as possible with regards to manufacturing. It is preferable to avoid CNC machining and just sticking to simple cutting, drilling and welding.

No loose/detachable parts
There should be no detachable parts that can be separated from the design. Loose part should also be avoided.

Fastening time
Since the physiotherapist might have about 5 to 10 patients a day using the machine, a minimal amount of time should be spent on attaching the head mount to the robot.

Chapter 6

Concepts

In the beginning of the specialization project, a meeting at Firda Physical-Medical Center was crucial. This gave very good insight on how things are done on a day to day basis regarding recovery training of patients and the operation of the MCU, as well as the anatomy of the human neck. Morten Leirgul, our contact at FPMC, is very eager on the development of this machine, and had a lot of suggestions and requirements regarding the design. Since I was alone on the project this year, it quickly became crucial to determine the extent of the assignment.

In product development, it is quite hard to make a detailed list or a plan on what to do and what not to do (see section 4.1). It is an ongoing process, and better solutions may emerge as you progress. However, there has been a tendency in the past projects on the development of this machine to ”test and discard”. This is of course important when assessing different solutions, but if the project is going to get somewhere, a final decision has to be made. During the time-frame of the specialization project, 3 different concepts regarding the machine has been investigated and are be further analyzed in the next 3 sections.

6.1 Panda by Franka Emika

In the Gaelok and Strand thesis, the best solution was based on a robotic arm from Franka Emika. Given their thorough research, a discussion with supervisor Knut Aasland was conducted, and we decided to go down to Munich to see the robot first hand, and what it could do. Our firs impressions of the robot was very good, although Morten Leirgul had some concerns about moving the robot freely without resistance. This could be solved in the programming software we were told. I also brought a modified helmet in hope of testing how the robot operates when connected to a human head, but the robots gripping hand was not fit to hold the helmet. Upon the return to Norway we decided that using the Panda robot as the motion platform was the way to go. The robot costs 9 900 Euro, which means we have to apply for funding. But since the platform is decided, we can move forward by settling on a suitable mounting mechanism between the patients head and the robot arm. This would also include further development of the head mount, as suggested under *future work* in the Gælok and Strand thesis[4].

Figure 6.1: Panda by Franka Emika[Author]

6.2 Head mount

After conversations with the project supervisor, the initial idea was to develop a partnership with a helmet production company and giving them the assignment of designing a custom head mount that could be used in the machine. On the recommendation from the Gælok and Strand thesis, we wanted a helmet with a solid outer shell, and an inner texture consisting of one or several inflatable elements depending on what works best.

6.2.1 Etto Twister

Contact was established with Fredrik Stormo at Scandinavias biggest helmet producer, Etto[32]. He was very interested in our project, and was frequently participating in the development of new helmet designs under the Etto brand. Unfortunately their involvement would come down to a question about money, and he estimated that a custom design meeting all of our requirements would need a lot of designing and testing hours before we would get a preferable product. More specific the price for this kind of project would very doubtfully go beneath 10 000 Euro.

Fredrik suggested that we should go for a current Etto ski helmet model, called Twister (see figure 6.2). He also revealed their main approach for making the helmets fit as many people as possible. Their research shows that the back of the head is the part that is most consistent in the different head shapes. They use this part of the head as the fixing point, where a fabric covered foam pad is used to presses the head upwards towards the top of the helmet, by the help of a turn knob. This way the head would be fixed between two points inside the helmet, and using inflatable elements instead of the fabric covered foam plate, would likely improve the fixture.

Figure 6.2: Etto Twister[9]

Using the Etto Twister as the base design of the head mount solved requirements with regards to a soothing and familiar design, as it is highly likely that the patients has worn or seen an alpine helmet before. The helmet is also fairly comfortable, and due to its spherical shell will offer a symmetrical fixture when implementing inflatable padding on the inside. This left three requirements for the inflatable padding, which needed to feature minimal play, easy attachment/detachment of head, and obviously fit different head shapes.

6.2.2 Bulb pump and inflatable neck pillow

One of the biggest questions was how to inflate the padding, and how to make this a procedure that the patient can do for him or herself. The prototypes from earlier involved a bicycle pump that delivers a small volume of air, but at a relatively high amount of pressure at each pumping cycle. Since it is unlikely that the padding would need an internal pressure as that of a bicycle wheel, a different type of pump should be used. As a solution a simple hand-held bulb pump was chosen. In this early stage, a fabric covered inflatable neck pillow would serve as the padding.

Figure 6.3: Bulb pump and inflatable neck pillow[Author]

6.2.3 Prototyping

The padding was then installed on the inside in the lower back part of the helmet, with a tube for the bulb pump sticking out. During the test, the helmet was placed in position around the head, and only 5 consecutive presses on the bulb pump was enough to get a very tight and sturdy fixture of the head. All in all the procedure took around 30 seconds. To remove the helmet, a simple twist on top of the bulb pump, lets all the air out of the padding. The only play that could be identified during the test was because of movement of the subcutaneous tissue, which is the part between the skull and outer skin. All in all the design shows great promise with regards to developing a finished product.

Figure 6.4: Prototype of the head mount[Author]

6.3 Mounting mechanism

The main part of the specialization project was developing a mounting mechanism between the robot arm, and the head mount, which is now the Etto Twister. The prototypes was developed using flexible product development (4.1), set based design (4.2) and CAD as design tools. With regards to set based design, there was two constrains that could not be modified. The first constrain is the the end effector of the robotic arm, consisting of a flange with a Ø50 bolt circle and four M6 threaded holes (appendix **??**). The second constrain is the mounting shim fixed on the back of the helmet.

6.3.1 Mounting shim

As the helmet has as spherical surface, a shim was needed to get a flat fixing surface for the mounting mechanism. This part was made using CAD and picture editing software to capture the shapes of the Etto helmet. On the helmet, there was two riveted nails made for the goggle holder. These where removed and replaced with two M5 bolts. The assembly proved very sturdy, and can be shown in the figure 6.5 below.

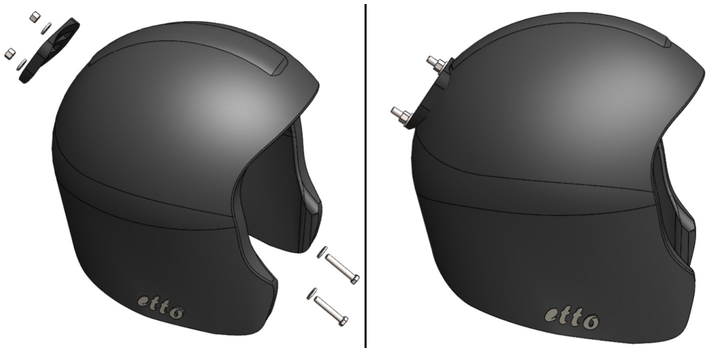

Figure 6.5: Helmet and shim assembly[Author]

The flat surface made the design process of the following solutions much easier. All in all it resulted in 5 different designs, and they are listed in the following sections together with a summary of their pros and cons.

6.3.2 Wing-head bolt design

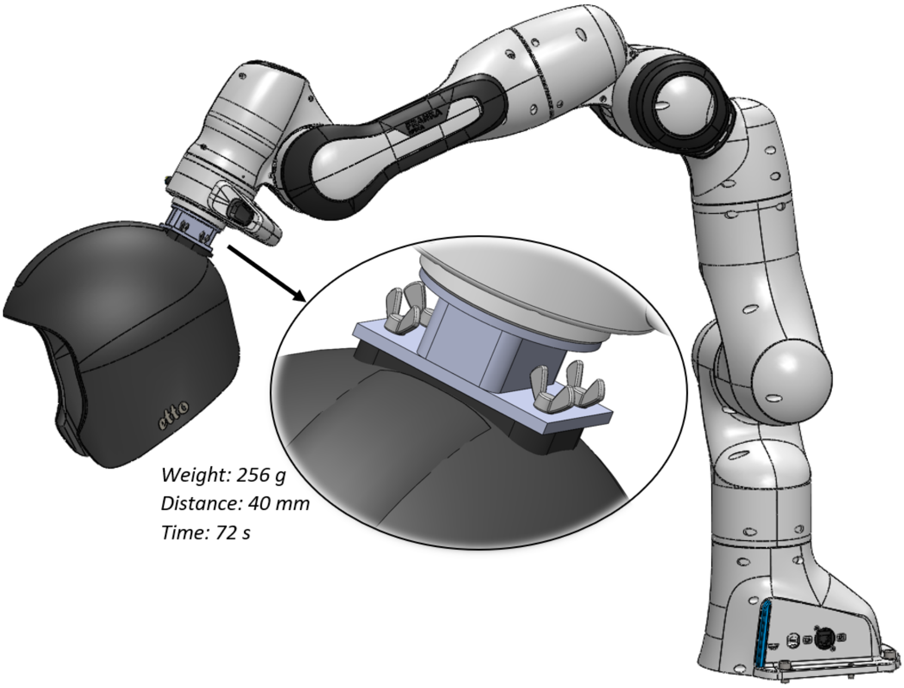

Figure 6.6: Wing-head bolt design[Author]

Summary: This design uses 4 pieces of wing-head bolts screwed into the mounting shim on the helmet. The design provides a very stiff connection, and will be easy to manufacture. It is also the lightest design. On the downside it will take a long time to fasten. An animation gives an estimated fastening time of over one minute, and that is under the condition that everything goes smoothly. Additionally, the four wing head bolts are loose parts when the helmet is not mounted, and can easily fall out of their holes and disappear.

6.3.3 Double draw latch design

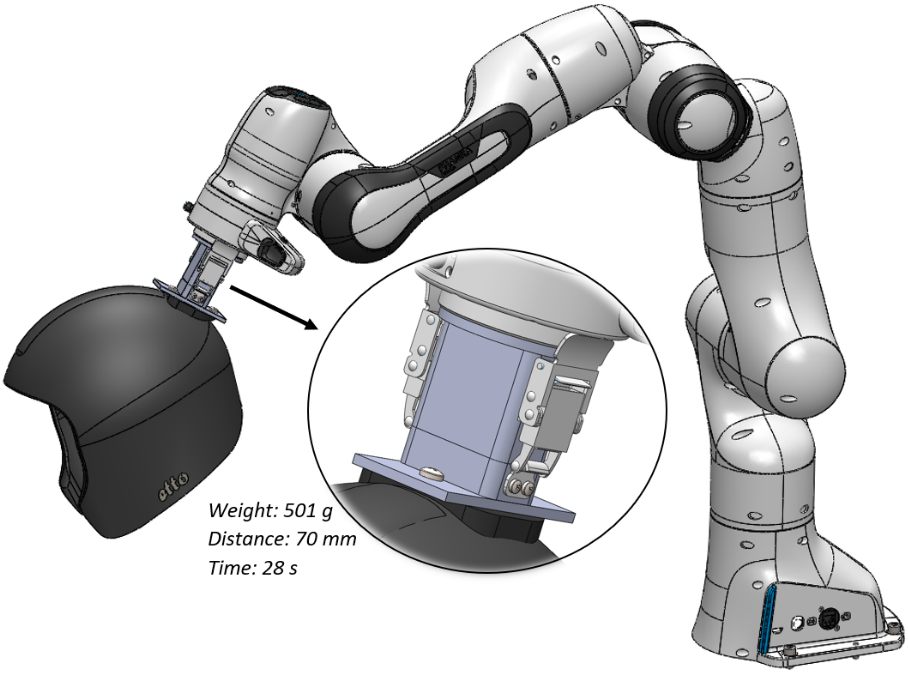

Figure 6.7: Double draw latch design[Author]

Summary: The double draw latch design has as the name suggests, two draw latches making a relatively stiff connection between the helmet and robot arm. The procedure of locking the mechanism can be tricky, but with a bit of practice it will be fully mounted in about 20 to 30 seconds. One major disadvantage is that the connection is fairly long, and will create an unwanted moment from the mounting shim and the end effector. This will most likely have a undesirable effect on the robots ability to provide appropriate resistance against the patients movement.

6.3.4 Sliding wing-head bolt design

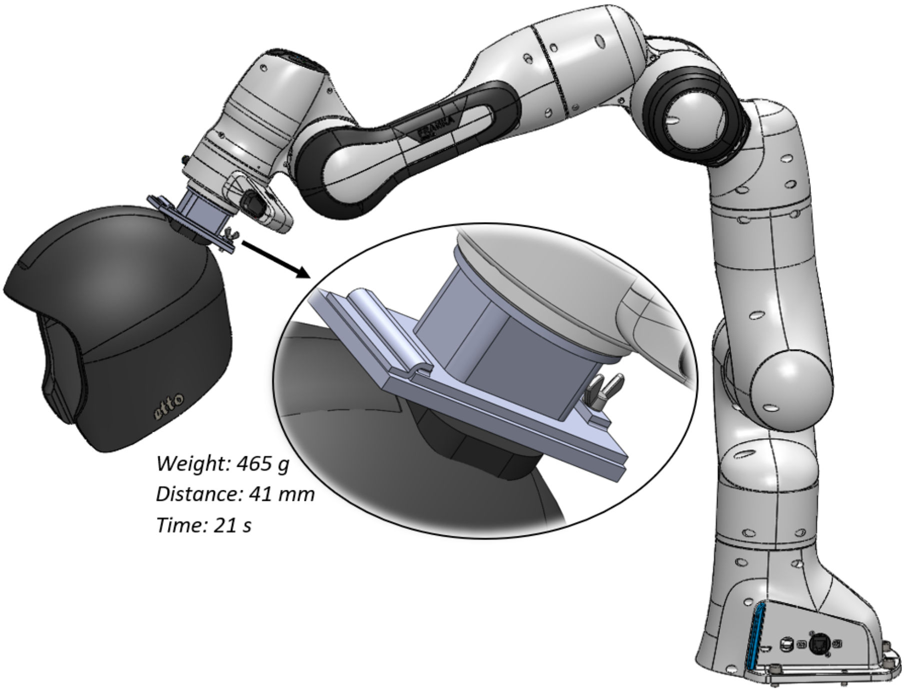

Figure 6.8: Sliding wing-head bolt design[Author]

Summary: The sliding mechanism works in the way that a small metal plate slides into a sheet metal hem from the left to the right side. This plate stops in its inner position due to another hem(not visible on picture) on the right side. In its inner position, the wing-head bolt is screwed into place, and locks the connection. By doing so, 3 wing-head bolts has been eliminated, and the fastening procedure goes much faster(around 20 seconds). The design still has loose parts when unmounted. Manufacturing the sheet metal hem is also more challenging.

6.3.5 Sliding draw latch design

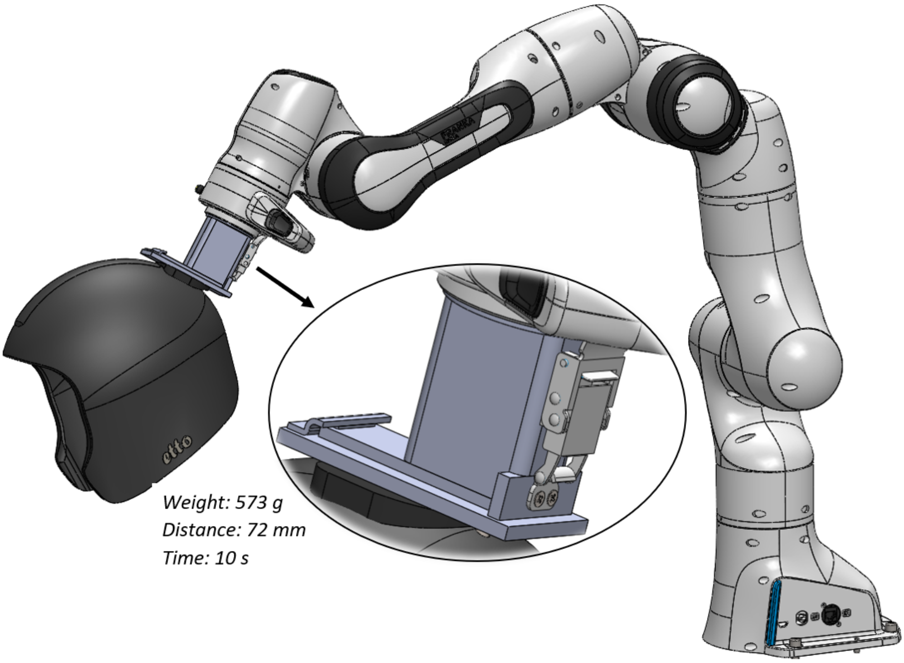

Figure 6.9: Sliding draw latch design[Author]

Summary: Same as the previous design. It is a sliding mechanism, but with a draw latch instead of a wing head bolt. This mechanism will be even faster for the physiotherapist to lock, with an estimated fastening time of 10 seconds. But the draw latch still causes the unwanted distance between the shim and end effector.

6.3.6 Sliding window latch design

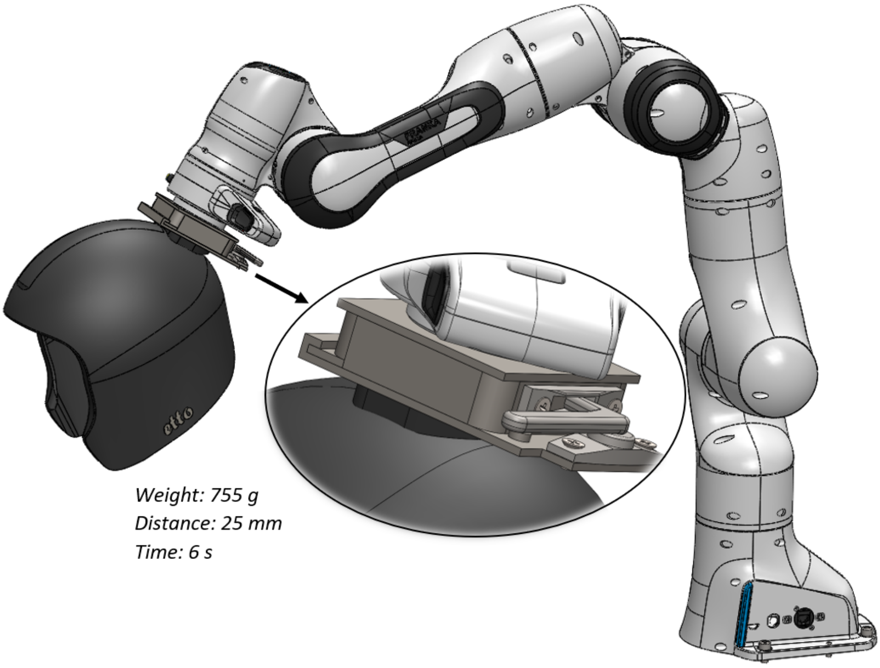

Figure 6.10: Sliding window latch design[Author]

Summary: Using a window latch eliminates the unwanted length created by the draw latch. It is also very easy to attach, and provides a very stiff connection. The downside of this design, is its weight and that it is more challenging to manufacture.

6.3.7 Evaluation

To help decide on a final design, a requirement table was made where all the designs are measured with regards to their performance. Each requirement from section 5.2 is given a certain amount of weight points (from 1 to 10) depending on their importance. They are then multiplied with the score given for each particular design.

Design requirements comparison table						
Product requirement	Weight points	Wing-head bolt design	Double draw latch design	Sliding wing-head bolt design	Sliding draw latch design	Sliding window latch design
No play	*8*	$\mathbf{9}\times 8 = 72$	$\mathbf{7}\times 8 = 56$	$\mathbf{8}\times 8 = 64$	$\mathbf{7}\times 8 = 56$	$\mathbf{8}\times 8 = 64$
Easy to attach/detach	*7*	$\mathbf{3}\times 7 = 21$	$\mathbf{5}\times 7 = 35$	$\mathbf{6}\times 7 = 42$	$\mathbf{8}\times 7 = 56$	$\mathbf{10}\times 7 = 70$
Lightweight	*6*	$\mathbf{10}\times 6 = 60$	$\mathbf{7}\times 6 = 42$	$\mathbf{6}\times 6 = 36$	$\mathbf{5}\times 6 = 30$	$\mathbf{4}\times 6 = 24$
Soothing design	*3*	$\mathbf{3}\times 3 = 9$	$\mathbf{6}\times 3 = 18$	$\mathbf{5}\times 3 = 15$	$\mathbf{6}\times 3 = 18$	$\mathbf{7}\times 3 = 21$
Easy to manufacture	*3*	$\mathbf{10}\times 3 = 30$	$\mathbf{6}\times 3 = 18$	$\mathbf{5}\times 3 = 15$	$\mathbf{5}\times 3 = 15$	$\mathbf{3}\times 3 = 9$
No loose parts	*5*	$\mathbf{3}\times 5 = 15$	$\mathbf{6}\times 5 = 30$	$\mathbf{6}\times 5 = 30$	$\mathbf{8}\times 5 = 40$	$\mathbf{10}\times 5 = 50$
Fastening time	*6*	$\mathbf{2}\times 6 = 12$	$\mathbf{5}\times 6 = 30$	$\mathbf{6}\times 6 = 36$	$\mathbf{7}\times 6 = 42$	$\mathbf{10}\times 6 = 60$
Final score	*max 380*	**219**/380	**229**/380	**238** /380	**257**/380	**298**/380

Table 6.1: Requirements table

The sliding window latch design gets the highest overall score. It is seen to be very sturdy and provides he best solution with regards to minimizing the distance between the helmet and end effector. The animation of the fastening time shows only 6 seconds, which is incredibly fast. To test the design physically, a functional prototypes was 3D printed in PLA, a common 3D printing material. It showed great potential. When the mechanism was locked using the window latch, it would not move at all. Additionally, it proved very easy to slide the top part into the bottom part. By consulting with both the supervisor Knut Aasland, and Morten Leirgul from FPMC, it was decided to move forwards with the design.

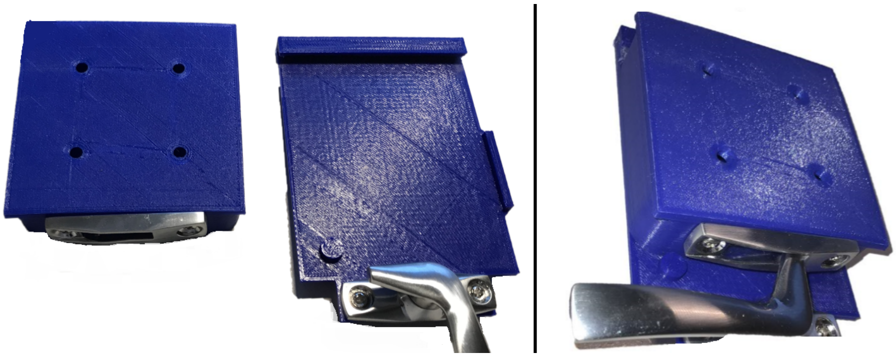

Figure 6.11: 3D printed model[Author]

6.3.8 Solution

The sliding window latch design was manufactured using 3 mm sheet metal and a 80x40x3mm rectangular beam. The material is 316 stainless steel. The density of stainless steel is around 8 grams per cubic cm giving the design a total weight of about 0.7 kg. The solution achieves better scores in all the product requirements except manufacturing and weight. When using the helmet with the mount attached, one can easily feel the inertia caused by the extra 0.7 kg.

However, the 3D printed model reduced weight down to only 0.1 kg and became nearly unnoticeable when using the helmet. The downside is that PLA wears out much faster, especially with regards to the sliding mechanism. PLA is also a biodegradable product, and has an expiration date. If the solution turns out to be too heavy, it is possible to produce it in aluminum, giving it an estimated weight of 0.2 kg. Additional shape optimization can also be done to remove unnecessary material, and make the size of the mechanism smaller. For now the design will stay as is until we can test it with the Panda robot.

Figure 6.12: Sliding window latch design in stainless steel[Author]

Chapter 7

Project evaluation

The initial plan for this semester was to have at least two students working on the specialization project. The project as a whole is very big, and doing it alone was initially quite challenging. The last three months have been hectic, but very fun. It started with a trip to Sandane to get a decent introduction to the project at FPMC. Afterwards a trip to Munich, which resulted in a final decision on the motion platform. Once the platform was in place, the project could be narrowed down to specific tasks. The following sections evaluates aspects on how the specialization project has been carried out.

7.1 Information assessment

The first month was used for reading and assessing former projects and master thesis. The amount and quality of the work that has been done by the past students has been of great value. The designs and prototypes tested in the past, has been the cornerstones for everything that has been done during this project, and it would not be possible to get this far without it. As the project progressed, information was gathered as needed by the use of phone interviews, e-mails and the web. Morten at FPMC has always been available for questions or updates regarding the machine. Weekly meetings has also been conducted with the supervisor, Knut. Questions about the Panda robot was communicated though mail with Carlo Bagnato, from Franka Emika.

As stated, the main challenge was being alone on the project. The project requires knowledge on topics like robotics, mechanics and the human anatomy. By being alone, all the information is only processed through one individual, and eliminates the much needed discussions and assessments. This resulted in more fact checking and more time spent gathering information and cross checking references.

7.2 Planning

Being alone has its upsides with regards to planning. In the very beginning of the semester, I made a detailed to-do list for the period. Each major activity was divided into smaller segments for each week. As detailed planning is quite challenging in product development, it almost always resulted in doing more than was initially intended. This turned out to be a great recourse at he end of the period. What initially was supposed to be a project about the mounting mechanism, resulted in additional work towards a working head mount prototype. The responsibility of finishing the assignment lay solely on myself, which opened possibility to work when I wanted, how I wanted.

7.3 Summary

I started the project with little to no knowledge about whiplash and neck related injuries, and used well over a month researching the topic along with the previous work. The specialization project has made this semester one of the most interesting since I started studying. It is highly motivating working on solutions that potentially can help a lot of people. With focus on flexible product development, set-based design and prototyping, there was no jumping to conclusions early in the process, and final decisions was made close to a month before delivery.

All in all I think the project turned out much better than expected, and has paved the road well with regards to my master thesis. One of the main motivating factors was the general interest and enthusiasm from both the supervisor Knut, and Morten from FPMC. Since I started the project, I have said that my goal is to have a finished prototype of the machine by June 2018, and it is my impression that this is well within reach.

Chapter 8

Future work

The master thesis will pick up where this specialization project left off. The mounting mechanism is now classified as a finished product, and will not be further developed unless absolutely necessary because of its weight and size as stated in section 6.3.8. There are mainly three major parts of the machine left for development, and they are listed in the following sections.

8.1 Head mount

The head mount consisting of an Etto alpine helmet showed great potential, and must be developed further. Especially with regards to the inflatable elements. A final decisions on the number of elements, their placements inside the helmet and the size must be established. The best approach for reaching an optimal product, will be to test the designs through prototyping. Before the design is finalized it should be tested on several people, thus assuring that it will fit everyone.

8.2 Seat

The seat which was first started on in the Kirkeeide thesis(2.3), must be further developed. There still has not been a working prototype on this part of the machine. If the design should go towards a seat or a modular based design is unclear, and advantages/disadvantages must be assessed. The design had a lot of electrical actuators used for adjusting the seat in different positions. It will be necessary to simplify it, and use simple manual adjustments on the smaller components of the seat, like the elbow height and back supports. Arrangement for installing of the actuators at a later time should be made.

8.3 Platform framework

Since the platform of the machine is going to be the Panda robot, a structure for securing it in place must be developed. Solutions investigating if this structure should be a part of the seat or not, must be looked at. The most important part is that the framework is stable, and impossible to flip over. It should also grant a decent and strong fixture of the robots base.

8.4 Panda robot arm

There is a lot of work to be done regarding programming of the robot arm, and this will most likely have to be separate project for students studying cybernetics- and computer engineering. There is also the question about receiving funds to buy the robot.

8.5 Summary

Looking back on what has been done, it is clear that the project is well underway. The remaining work on the mechanical side of things is viewed as manageable within the time frame of the master thesis, and the plan to have a completely finished prototype by June 2018 is still standing.

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Appendix I

Risk assessment

ID	23743	**Status**	**Dato**
Risikoområde	Risikovurdering: Helse, miljø og sikkerhet (HMS)	Opprettet	17.10.2017
Opprettet av	Stian Krogstad Brattgjerd	Vurdering startet	17.10.2017
Ansvarlig	Stian Krogstad Brattgjerd	Tiltak besluttet	17.10.2017
		Avsluttet	17.10.2017

Risikovurdering:

Risikorapport i forhold til verkstedvirksomhet og prototyping

Gyldig i perioden:

-

Sted:

Verkstedteknisk, Gløshaugen

Mål / hensikt

Utvikle en prototype for rehabilitering av nakkeslengskadde

Bakgrunn

Prosjekt- og master oppgave 207/2018

Beskrivelse og avgrensninger

Arbeid på verksted

Forutsetninger, antakelser og forenklinger

HMS-kurs og verkstedkurs

Vedlegg

[Ingen registreringer]

Referanser

[Ingen registreringer]

Stian K. Brattgjerd

Oppsummering, resultat og endelig vurdering

I oppsummeringen presenteres en oversikt over farer og uønskede hendelser, samt resultat for det enkelte konsekvensområdet.

Farekilde: **Klemskade**

Uønsket hendelse: **Fingre/føtter kommer i klem**

Konsekvensområde: Helse — Risiko før tiltak: 🟢 Risiko etter tiltak: 🟢

Risikoreduserende tiltak	Ansvarlig	Registrert	Frist	Status
Personlig verneutstyr	Stian Krogstad Brattgjerd	17.10.2017	17.10.2017	Nytt
HMS og praksiskurs	Stian Krogstad Brattgjerd	17.10.2017	17.10.2017	Nytt

Farekilde: **Kuttskade**

Uønsket hendelse: **Kuttskade ved dreiespon eller kniv**

Konsekvensområde: Helse — Risiko før tiltak: 🟢 Risiko etter tiltak: 🟢

Risikoreduserende tiltak	Ansvarlig	Registrert	Frist	Status
Personlig verneutstyr	Stian Krogstad Brattgjerd	17.10.2017	17.10.2017	Nytt
HMS og praksiskurs	Stian Krogstad Brattgjerd	17.10.2017	17.10.2017	Nytt

Farekilde: **Brennskade**

Uønsket hendelse: **Sveising uten vernehansker**

Konsekvensområde: Helse — Risiko før tiltak: 🟢 Risiko etter tiltak: 🟢

Risikoreduserende tiltak	Ansvarlig	Registrert	Frist	Status
Personlig verneutstyr	Stian Krogstad Brattgjerd	17.10.2017	17.10.2017	Nytt
HMS og praksiskurs	Stian Krogstad Brattgjerd	17.10.2017	17.10.2017	Nytt

Farekilde: **Gassforgiftning**

Uønsket hendelse: **Dårlig eller ingen avtrekk for giftige gasser**

Konsekvensområde: Helse — Risiko før tiltak: 🟡 Risiko etter tiltak: 🟢

Risikoreduserende tiltak	Ansvarlig	Registrert	Frist	Status
Personlig verneutstyr	Stian Krogstad Brattgjerd	17.10.2017	17.10.2017	Nytt
HMS og praksiskurs	Stian Krogstad Brattgjerd	17.10.2017		Nytt

Farekilde: **Feil bruk av maskiner**

Uønsket hendelse: **Skade på maskin eller personell**

Konsekvensområde:			
Helse	Risiko før tiltak: 🟢	Risiko etter tiltak: 🟢	
Materielle verdier	Risiko før tiltak: 🟡	Risiko etter tiltak: 🟢	

Risikoreduserende tiltak	**Ansvarlig**	**Registrert**	**Frist**	**Status**
Opplæring og praksiskurs	Stian Krogstad Brattgjerd	17.10.2017	17.10.2017	Nytt

Farekilde: **Øyeskade**

Uønsket hendelse: **Dreiespon eller kjemikalier på øyet**

Konsekvensområde:		
Helse	Risiko før tiltak: 🟡	Risiko etter tiltak: 🟡

Risikoreduserende tiltak	**Ansvarlig**	**Registrert**	**Frist**	**Status**
HMS og praksiskurs	Stian Krogstad Brattgjerd	17.10.2017	17.10.2017	Nytt
Personlig verneutstyr	Stian Krogstad Brattgjerd	17.10.2017		Nytt

Endelig vurdering

Alle farekilder uten at øyeskade har en akseptabel risiko. Risikoen for øyeskade er lite sannsynlig, men utfallet om det skulle skje kan være ille. Man bør derfor være ekstra påpasselig med bruk av verne briller , og eventuelt bruke verneskjerm om nødvendig.

Involverte enheter og personer

En risikovurdering kan gjelde for en, eller flere enheter i organisasjonen. Denne oversikten presenterer involverte enheter og personell for gjeldende risikovurdering.

Enhet /-er risikovurderingen omfatter

- Institutt for maskinteknikk og produksjon

Deltakere

[Ingen registreringer]

Lesere

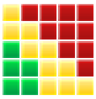
Knut Einar Aasland

Andre involverte/interessenter

Morten Leirgul, Firda fysmed

Følgende akseptkriterier er besluttet for risikoområdet Risikovurdering: Helse, miljø og sikkerhet (HMS):

Helse



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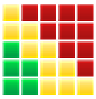
Materielle verdier



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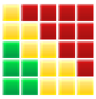
Omdømme



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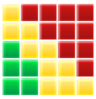
Ytre miljø



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🟩	🟩	🟨	🟨	🟨

Oversikt over eksisterende, relevante tiltak som er hensyntatt i risikovurderingen

I tabellen under presenteres eksisterende tiltak som er hensyntatt ved vurdering av sannsynlighet og konsekvens for aktuelle uønskede hendelser.

Farekilde	**Uønsket hendelse**	**Tiltak hensyntatt ved vurdering**
Klemskade	Fingre/føtter kommer i klem	Verneutstyr
Kuttskade	Kuttskade ved dreiespon eller kniv	Verneutstyr
	Kuttskade ved dreiespon eller kniv	Retningslinjer ved bruk av utstyr
Brennskade	Sveising uten vernehansker	Verneutstyr
	Sveising uten vernehansker	Avtrekk ved avgasser
Gassforgiftning	Dårlig eller ingen avtrekk for giftige gasser	Avtrekk ved avgasser
Feil bruk av maskiner	Skade på maskin eller personell	Verneutstyr
	Skade på maskin eller personell	Retningslinjer ved bruk av utstyr
	Skade på maskin eller personell	Personell på verksted
Øyeskade	Dreiespon eller kjemikalier på øyet	Verneutstyr
	Dreiespon eller kjemikalier på øyet	Retningslinjer ved bruk av utstyr

Eksisterende og relevante tiltak med beskrivelse:

Verneutstyr
[Ingen registreringer]

Avtrekk ved avgasser
[Ingen registreringer]

Retningslinjer ved bruk av utstyr
[Ingen registreringer]

Personell på verksted
[Ingen registreringer]

Risikoanalyse med vurdering av sannsynlighet og konsekvens

I denne delen av rapporten presenteres detaljer dokumentasjon av de farer, uønskede hendelser og årsaker som er vurdert. Innledningsvis oppsummeres farer med tilhørende uønskede hendelser som er tatt med i vurderingen.

Følgende farer og uønskede hendelser er vurdert i denne risikovurderingen:

- **Klemskade**
    - Fingre/føtter kommer i klem
- **Kuttskade**
    - Kuttskade ved dreiespon eller kniv
- **Brennskade**
    - Sveising uten vernehansker
- **Gassforgiftning**
    - Dårlig eller ingen avtrekk for giftige gasser
- **Feil bruk av maskiner**
    - Skade på maskin eller personell
- **Øyeskade**
    - Dreiespon eller kjemikalier på øyet

Detaljert oversikt over farekilder og uønskede hendelser:

Farekilde: Klemskade

Uønsket hendelse: Fingre/føtter kommer i klem

Årsak: Uoppmerksom

Årsak: Trøtt

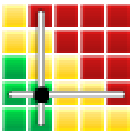
Sannsynlighet for hendelsen (felles for alle konsekvensområder): **Lite sannsynlig (2)**

Kommentar:

[Ingen registreringer]

Konsekvensområde: Helse

Risiko:



Vurdert konsekvens: **Middels (2)**

Kommentar: [Ingen registreringer]

Farekilde: Kuttskade

Uønsket hendelse: Kuttskade ved dreiespon eller kniv

Årsak: Feil bruk

Sannsynlighet for hendelsen (felles for alle konsekvensområder): **Lite sannsynlig (2)**

Kommentar:

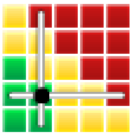
[Ingen registreringer]

Konsekvensområde: Helse

Vurdert konsekvens: **Middels (2)**

Kommentar: [Ingen registreringer]

Risiko:



Farekilde: Brennskade

Uønsket hendelse: Sveising uten vernehansker

Årsak: Feil bruk

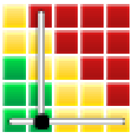
Sannsynlighet for hendelsen (felles for alle konsekvensområder): **Svært lite sannsynlig (1)**

Kommentar:

[Ingen registreringer]

Konsekvensområde: Helse

Risiko:



Vurdert konsekvens: **Middels (2)**

Kommentar: [Ingen registreringer]

Farekilde: Gassforgiftning

Uønsket hendelse: Dårlig eller ingen avtrekk for giftige gasser

Årsak: Ikke bruk av avtrekk

Sannsynlighet for hendelsen (felles for alle konsekvensområder): **Lite sannsynlig (2)**

Kommentar:

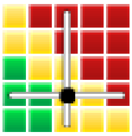
[Ingen registreringer]

Konsekvensområde: Helse

Vurdert konsekvens: **Stor (3)**

Kommentar: [Ingen registreringer]

Risiko:



Farekilde: Feil bruk av maskiner

Uønsket hendelse: Skade på maskin eller personell

Årsak: Ikke tilstrekkelig opplæring

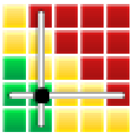
Sannsynlighet for hendelsen (felles for alle konsekvensområder): **Lite sannsynlig (2)**

Kommentar:

[Ingen registreringer]

Konsekvensområde: Helse

Risiko:

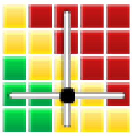


Vurdert konsekvens: **Middels (2)**

Kommentar: [Ingen registreringer]

Konsekvensområde: Materielle verdier

Risiko:



Vurdert konsekvens: **Stor (3)**

Kommentar: [Ingen registreringer]

Farekilde: Øyeskade

Uønsket hendelse: Dreiespon eller kjemikalier på øyet

Årsak: Spon på øyet

Årsak: Kjemiklaier på øyet

Sannsynlighet for hendelsen (felles for alle konsekvensområder): **Lite sannsynlig (2)**

Kommentar:

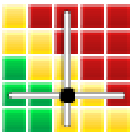
[Ingen registreringer]

Konsekvensområde: Helse

Vurdert konsekvens: **Stor (3)**

Kommentar: [Ingen registreringer]

Risiko:



Oversikt over besluttede risikoreduserende tiltak:

Under presenteres en oversikt over risikoreduserende tiltak som skal bidra til å reduseres sannsynlighet og/eller konsekvens for uønskede hendelser.

- Personlig verneutstyr
- HMS og praksiskurs
- Personlig verneutstyr
- HMS og praksiskurs
- Personlig verneutstyr
- HMS og praksiskurs
- Personlig verneutstyr
- HMS og praksiskurs
- Opplæring og praksiskurs
- HMS og praksiskurs
- Personlig verneutstyr

Detaljert oversikt over besluttede risikoreduserende tiltak med beskrivelse:

Personlig verneutstyr

Sørge for at personlig verneutstyr brukes.

Tiltak besluttet av:	Stian Krogstad Brattgjerd
Ansvarlig for gjennomføring:	Stian Krogstad Brattgjerd
Frist for gjennomføring:	10/17/2017

HMS og praksiskurs

Tiltak besluttet av:	Stian Krogstad Brattgjerd
Ansvarlig for gjennomføring:	Stian Krogstad Brattgjerd
Frist for gjennomføring:	10/17/2017

Personlig verneutstyr

Bruk av verneutstyr

Tiltak besluttet av:	Stian Krogstad Brattgjerd
Ansvarlig for gjennomføring:	Stian Krogstad Brattgjerd
Frist for gjennomføring:	10/17/2017

HMS og praksiskurs

Tiltak besluttet av:	Stian Krogstad Brattgjerd
Ansvarlig for gjennomføring:	Stian Krogstad Brattgjerd
Frist for gjennomføring:	10/17/2017

Personlig verneutstyr

Tiltak besluttet av:	Stian Krogstad Brattgjerd
Ansvarlig for gjennomføring:	Stian Krogstad Brattgjerd
Frist for gjennomføring:	10/17/2017

HMS og praksiskurs

Tiltak besluttet av:	Stian Krogstad Brattgjerd
Ansvarlig for gjennomføring:	Stian Krogstad Brattgjerd
Frist for gjennomføring:	10/17/2017

Personlig verneutstyr

ånderettsvern

Tiltak besluttet av:	Stian Krogstad Brattgjerd
Ansvarlig for gjennomføring:	Stian Krogstad Brattgjerd
Frist for gjennomføring:	10/17/2017

HMS og praksiskurs

Tiltak besluttet av:	Stian Krogstad Brattgjerd
Ansvarlig for gjennomføring:	Stian Krogstad Brattgjerd
Frist for gjennomføring:	

Opplæring og praksiskurs

Tiltak besluttet av:	Stian Krogstad Brattgjerd
Ansvarlig for gjennomføring:	Stian Krogstad Brattgjerd
Frist for gjennomføring:	10/17/2017

HMS og praksiskurs

Tiltak besluttet av:	Stian Krogstad Brattgjerd
Ansvarlig for gjennomføring:	Stian Krogstad Brattgjerd
Frist for gjennomføring:	10/17/2017

Personlig verneutstyr

vernebriller

Tiltak besluttet av:	Stian Krogstad Brattgjerd
Ansvarlig for gjennomføring:	Stian Krogstad Brattgjerd
Frist for gjennomføring:	

Detaljert oversikt over vurdert risiko for hver farekilde/uønsket hendelse før og etter besluttede tiltak

Farekilde: **Klemskade**

Uønsket hendelse: **Fingre/føtter kommer i klem**

Sannsynlighetsvurderinger (felles for alle konsekvensområder):

Opprinnelig sannsynlighet: Lite sannsynlig (2)

Begrunnelse:

Sannsynlighet etter tiltak: Lite sannsynlig (2)

Begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: **Helse**

Risiko:

Opprinnelig konsekvens: Middels (2)

Begrunnelse:

Konsekvens etter tiltak: Middels (2)

Begrunnelse:

Farekilde: **Kuttskade**

Uønsket hendelse: **Kuttskade ved dreiespon eller kniv**

Sannsynlighetsvurderinger (felles for alle konsekvensområder):

Opprinnelig sannsynlighet: Lite sannsynlig (2)

Begrunnelse:

Sannsynlighet etter tiltak: Lite sannsynlig (2)

Begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: **Helse**

Risiko:

Opprinnelig konsekvens: Middels (2)

Begrunnelse:

Konsekvens etter tiltak: Middels (2)

Begrunnelse:

Farekilde: **Brennskade**

Uønsket hendelse: **Sveising uten vernehansker**

Sannsynlighetsvurderinger (felles for alle konsekvensområder):

Opprinnelig sannsynlighet: Svært lite sannsynlig (1)

Begrunnelse:

Sannsynlighet etter tiltak: Svært lite sannsynlig (1)

Begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: **Helse**

Risiko:

Opprinnelig konsekvens: Middels (2)

Begrunnelse:

Konsekvens etter tiltak: Liten (1)

Begrunnelse:

Farekilde: **Gassforgiftning**

Uønsket hendelse: **Dårlig eller ingen avtrekk for giftige gasser**

Sannsynlighetsvurderinger (felles for alle konsekvensområder):

Opprinnelig sannsynlighet: Lite sannsynlig (2)

Begrunnelse:

Sannsynlighet etter tiltak: Lite sannsynlig (2)

Begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: **Helse**

Risiko:

Opprinnelig konsekvens: Stor (3)

Begrunnelse:

Konsekvens etter tiltak: Middels (2)

Begrunnelse:

Farekilde: **Feil bruk av maskiner**

Uønsket hendelse: **Skade på maskin eller personell**

Sannsynlighetsvurderinger (felles for alle konsekvensområder):

Opprinnelig sannsynlighet: Lite sannsynlig (2)

Begrunnelse:

Sannsynlighet etter tiltak: Lite sannsynlig (2)

Begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: **Helse**

Risiko:

Opprinnelig konsekvens: Middels (2)

Begrunnelse:

Konsekvens etter tiltak: Middels (2)

Begrunnelse:

Konsekvensområde: **Materielle verdier**

Risiko:

Opprinnelig konsekvens: Stor (3)

Begrunnelse:

Konsekvens etter tiltak: Middels (2)

Begrunnelse:

Farekilde: **Øyeskade**

Uønsket hendelse: **Dreiespon eller kjemikalier på øyet**

Sannsynlighetsvurderinger (felles for alle konsekvensområder):

Opprinnelig sannsynlighet: Lite sannsynlig (2)

Begrunnelse:

Sannsynlighet etter tiltak: Lite sannsynlig (2)

Begrunnelse:

Konsekvensvurderinger:

Konsekvensområde: **Helse**

Risiko:

Opprinnelig konsekvens: Stor (3)

Begrunnelse:

Konsekvens etter tiltak: Stor (3)

Begrunnelse: