UiT The Arctic University of Norway

Faculty of Engineering Science and Technology

Design of Concept Joints for Future Patient Simulators

Development of a Shoulder Joint

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Master’s thesis in Engineering Design END-3900 May 2024

Acknowledgement

This thesis was written in spring 2024 and is the conclusive work of Design Engineering at UiT campus Narvik. The thesis is done in collaboration with Laerdal Medical.

The goal of the thesis is to develop a concept for a shoulder joint that can work in their upcoming patient simulators mimicking the functions of a human shoulder. The thesis shall reflect a completed course of study by showcasing the knowledge and tools acquired.

I want to thank my supervisor, Annette Meidell, for all the guidance during the thesis. I would also like to thank the Head of Study, Guy Beeri Mauseth, for his support and guidance during my two years.

I would also like to thank Laerdal Medical for giving me my first internships and an interesting thesis. Without them this thesis would not exist. I want to thank my supervisors from Laerdal, Andreas Kråkenes and Marius Auflem, for their continued guidance and support.

Lastly, I want to thank Silje Østeraas for her continued support and motivation throughout my studies.

Thank you.

Abstract

This thesis goes through the product development process for a shoulder joint meant for a future patient simulator for Laerdal Medical. The process focuses on the methodology taught during the masters’ degree for how an idea can be developed into a product.

Chapter 1 is regarded as the preliminary work and is an introduction to the thesis for the reader. Chapter 2 covers the methodology learnt during the masters’ degree and goes over how it’s been utilized for this thesis. It shows the methods and strategies utilized to develop the shoulder systematically.

Following is chapter 3 covering the material choices done for the product. The material was selected using the software Granta Edupack.

Chapter 4 goes into the analysis of the construction. The analysis makes assumptions and simplifications of the case studies for the sake of the thesis. The numerical analysis utilizes CAD-program Solidworks and shows us the stresses and deformation of the shoulder after the load is applied.

Chapter 5 and 6 covers the results and discussion respectively. The results didn’t go as expected, and some of it was resolved in the discussion.

Lastly, chapter 7 concludes the thesis. The product became the culmination of a methodical approach to concept development. The product still needs some development and testing before it is complete, but the concept is done.

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1 Introduction

Laerdal Medical started out as a small publishing and toy company in Stavanger founded by Åsmund S. Lærdal in 1940, but has since the 1960s developed and produced medical equipment and patient simulators for use in training civilians and healthcare workers in basic resuscitation (Tjomsland, 1990). Newer patient simulators are designed more specifically towards the healthcare sector and incorporate more advanced functions to imitate real life patients and more complex problems. Their most famous product is the Resusci Anne which was first presented in 1960 and has since then travelled the world as a cardiopulmonary resuscitation training simulator (Figure 1). Laerdal Medical have since then created a plethora of variants of training simulators out of which many are still in production and being sold in addition to certified medical equipment like the defibrillator and resuscitator (Laerdal, n.d.).

Figure 1: Resusci Anne family (National First Aid, n.d.)

1.1 Problem Description

Patient simulators are human-like robots utilized in a variety of scenarios and training routines within medical and healthcare education. Hence, they are subject to various loads from being handled, transported, and interacted with. The simulators require articulated joints to achieve realistic and human-like range of movement.

1.1.1 Problems to Solve

This task entails creating a concept for shoulder joints for future simulators, enabling fluid and electrical connections to pass through, as well as handling the various loading conditions and movements. The task will entail a literary study, establishing a case study, analytically estimate the loading conditions for these joints, systematic engineering design method, material selection, 3D-modelling and simulation and suggestions for future work.

1.2 Design Requirements

To make both a reliable product and to focus the aim for the thesis it is important to set some requirements. Many products follow standards based on their use and their safety importance. In this case the product would need a standard CE-approval to sell in the EU that includes the safety standard IEC62368-1 which covers most safety concerns like pinch hazard, and has, in accordance with Laerdal, been decided is the only relevant standard for us to consider. For this thesis the most important requirements are the design space, strength and design of the joint and the movement/degrees of freedom (DOF).

1.2.1 Design Space

The space available in the simulator is an important requirement due to the structure of the simulator. The shoulder joint is placed between the arm and the main bodyframe and is encapsulated in the skin of the simulator. This means there is a given maximum space available. In general, the sizes of adult human bodies vary individually based on factors like gender and muscle mass. The size of the joint that will be used in this thesis are based on a private STL-file borrowed from Laerdal that replicates the adult human body. As there is also need for cables that transport air, fluids and power to go through the shoulder joint there is also a need to create a safe way for the cables to move without blocking or destroying the cables. The three cables have a diameter of approximately 5mm each.

There is also a need to define the variables assigned to the space available. The measurements for the shoulder joint are not absolute because sizes vary among humans and the joint might be produced as part of the arm or the main frame when incorporated in the patient simulator. However, there is a need to define some limits for the shoulder area for the thesis. The following figure (Figure 2) shows the variables measured from the STL-file and the mean values are as follows: Width=90mm, Height=130mm, Length (Depth)=75mm. It can then be assumed this to be the maximum limits for the space available.

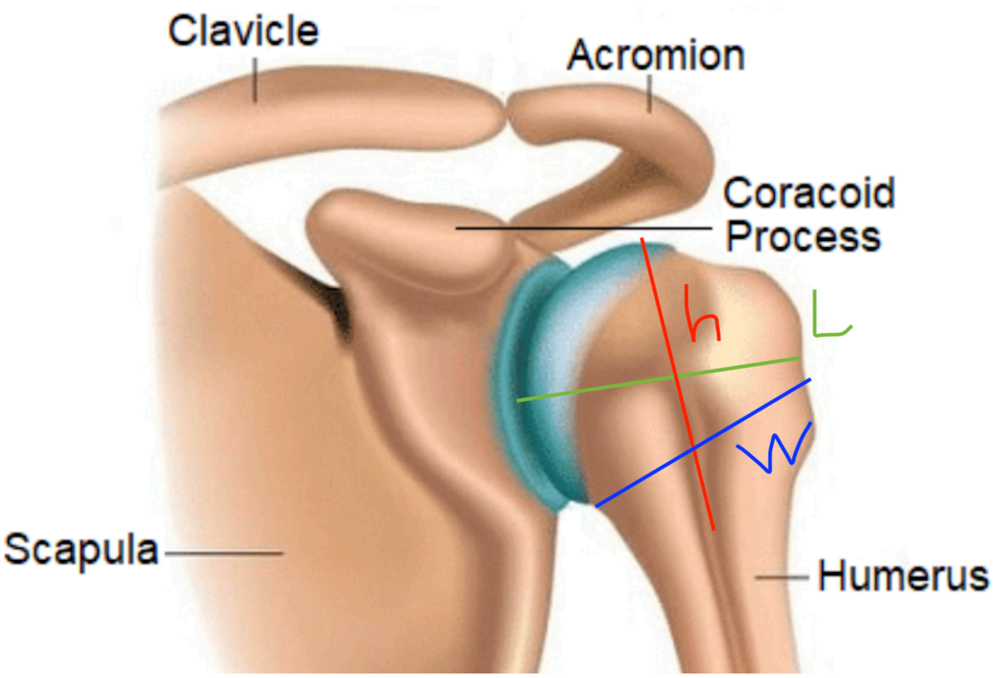

*Figure 2: Size Variable (*Wilson, 2022*)*

1.2.2 Joint Strength

The joint should be able to tolerate the external force acting upon it. The simulators are usually used indoors on a hospital bed, but they are also used in survival scenarios outdoors being dragged by the arm, carried on the back, thrown on the ground etc. In some of these cases there will be a force acting in the longitudinal direction of the arm being dragged/pulled plus in some cases the friction from the ground both of which results in tension in the arm and joint. The loading conditions acting on the joint will be determined analytically and confirmed with a 3D FEM simulation that will show us the resulting stress which will be of importance when designing the joint. I will evaluate one case study based on realistic use for strength simulations. This will be described in more detail in the next chapter "Case Study".

1.2.3 Degrees of Freedom

The degrees of freedom (DOF) are an important issue as the joint must replicate a realistic movement of the human shoulder incorporating the same DOF. This movement is in part possible due to the ball joint humans have. However, the mechanical joint for the simulator does not have to replicate the human joint but rather exhibit the same movement as the human joint in a mechanical solution. The human shoulder has the following three degrees of freedom that should be relayed in the mechanical joint; 1: Extension-Flexion, 2: Adduction-Abduction, 3: Internal rotation-External rotation. See picture below for a visual guide of the degrees of freedom, from 1 on the left to 3 on the right (Figure 3).

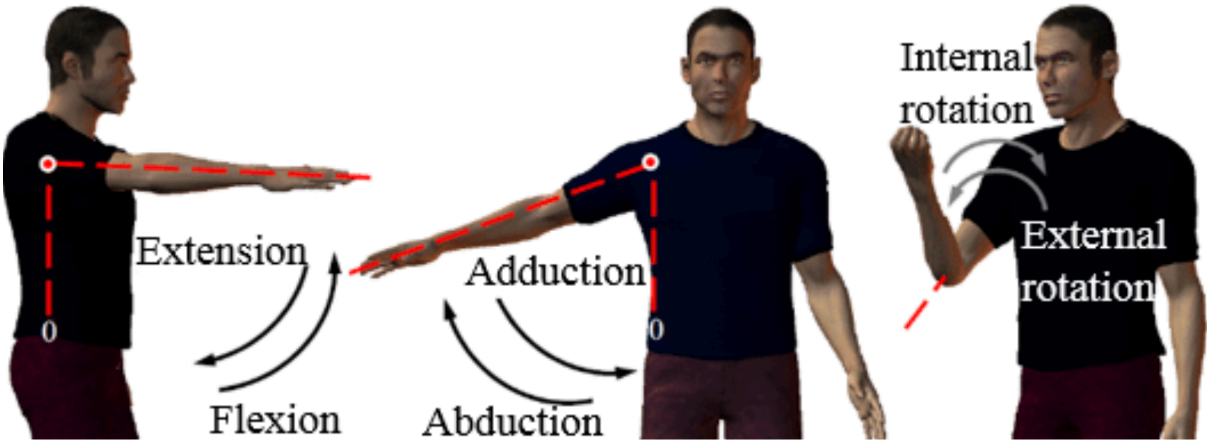

*Figure 3: Movement of Shoulder (*Weerakkody*, 2017)*

1.2.4 Other Requirements

The other requirements are somewhat flexible, but general guidelines that should be taken into consideration as well are weight, operational temperature, cost, number of parts, durability and fabrication process. These will be relevant for the process of choosing material for the joint which will be performed with the aid of Granta Edupack.

1.3 Case Study

I will in this task approach the design process using a pre-defined case study defined in chapter 1.3.1. A situation where the shoulders need to be robust will for instance be in the case of the "patient" being dragged by the arms while still on the ground. This can be replicated in 3D FEM simulations using correctly placed loading conditions and movement restrictions. The scenario can be calculated using numerical and analytical computations to confirm the results. The scenario chosen are in accordance with Laerdal and based on real life survival situations.

1.3.1 Dragged by the arm

For this scenario the patient is dragged by both arms in a supine position probably unconscious (See Figure 4 below). This can be simulated in a CAD-program by placing the constraint on the shoulder joint where it is connected to the body and the right forces in the approximate angle of the arm and the friction from the ground. Assume ground friction set at μ=0.45 as friction (Rasmussen, Medbø and Heimburg, 2007) as environment will vary, and using the weight of the adult-sized patient-simulator "SimMan3G", m=40kg, then use it to calculate an approximate force used to drag the patient:

$$|\vec{F}| = \frac{\mu m g}{\cos\theta + \mu \sin\theta} = \frac{0.45 * 40 * 9.81}{\cos 45 + 0.45 * \sin 45} = 1682N$$

where F is the force used when moving the patient, g is the gravitational force, and θ is the angle between the arm and the ground. It is also assumed that there is no slip and constant friction.

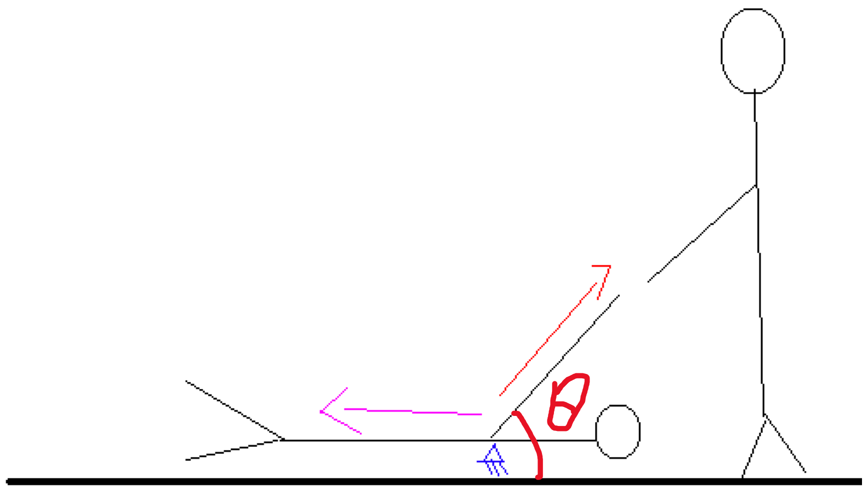

Figure 4: Case Study

1.4 Requirement Specifications

Some of the numbers presented here are approximations but are meant to give a rough idea of what the metrics are. The joint itself might in the end be a natural part of the humerus or the scapula depending on the joint, so the size might be flexible in that sense. The movement of the joint is also an approximation due to human nature the flexibility varies individually, so the values are guidelines, not absolutes. The three minimum DOF-values are based on information from Laerdal, and the ideal values are from *Healthline* (Sawyers, 2018). The maximum size values are based on the STL-file mentioned earlier. See Table 1 below for the requirement specifications.

Requirement Specifications	
Maximum Height	130mm
Maximum Width	90mm
Maximum Length	75mm
Arm Angle: Case Study	45°
Force: Case Study	1682N
Ground Friction Coefficient [μ]	0.45
Functionable Temperatures	Between -30°C and 40°C
Minimum Flexion (Ideal)	160° (180°)
Minimum Extension (Ideal)	30° (45°-60°)
Minimum Abduction (Ideal)	70° (150°)
Minimum Adduction (Ideal)	0° (30°)
Minimum Internal Rotation (Ideal)	90° (90°)
Minimum External Rotation (Ideal)	90° (90°)

Table 1: Requirement Specifications

1.5 Goal for the thesis

The aim of the thesis is to explore different concepts for a shoulder joint that fits the criteria of the task and move forward with one (or more) of these concepts and develop it using methods from engineering design.

1.6 Timeline

A timeline was to be created as part of the preliminary work for the thesis (Figure 5). This was meant to give a general plan for the student to follow when working on the thesis. It is based on estimates as to how long each part would take to finish assuming the work week of a normal full-time student. It was also meant to act as a guideline and reminder of how much time can be allocated to different parts where more important or time-consuming parts were given more weeks to work on.

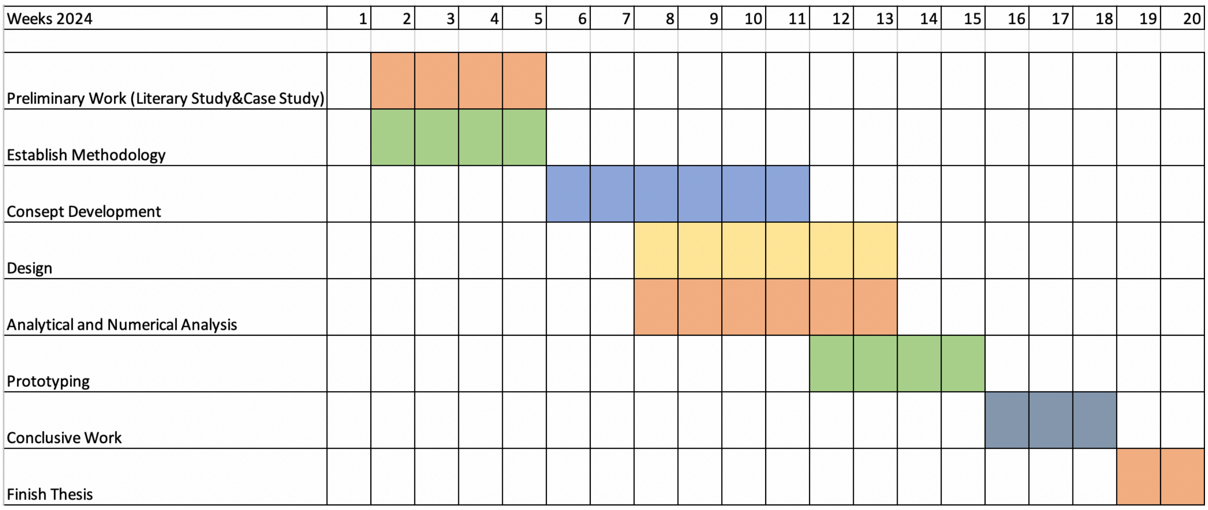

Figure 5: Timeline

2 Methodology

2.1 Introduction

In the realm of engineering, particularly within product development projects, adopting a systematic approach is detrimental. Such an approach provides a structured framework for managing the project which gives the user more efficiency and structure while working. Through the systematic definition of objectives and the methodical addressing of challenges, individuals maintain focus and are provided with clear boundaries within their tasks.

This thesis is going to be using the Nigel Cross design method (Cross, 2008) for developing the product. The Nigel Cross design method is a rational method for developing products commonly used in projects where function is more important than form. It has some common traits with some creative methods as they all try to find the best solution while keeping the solution space sufficiently wide. This method breaks the problems down into eight sub-problems for the user to follow that helps keep track of the progress while making sure nothing is forgotten (see Figure 6 below). I'll cover the all the steps in the coming chapters.

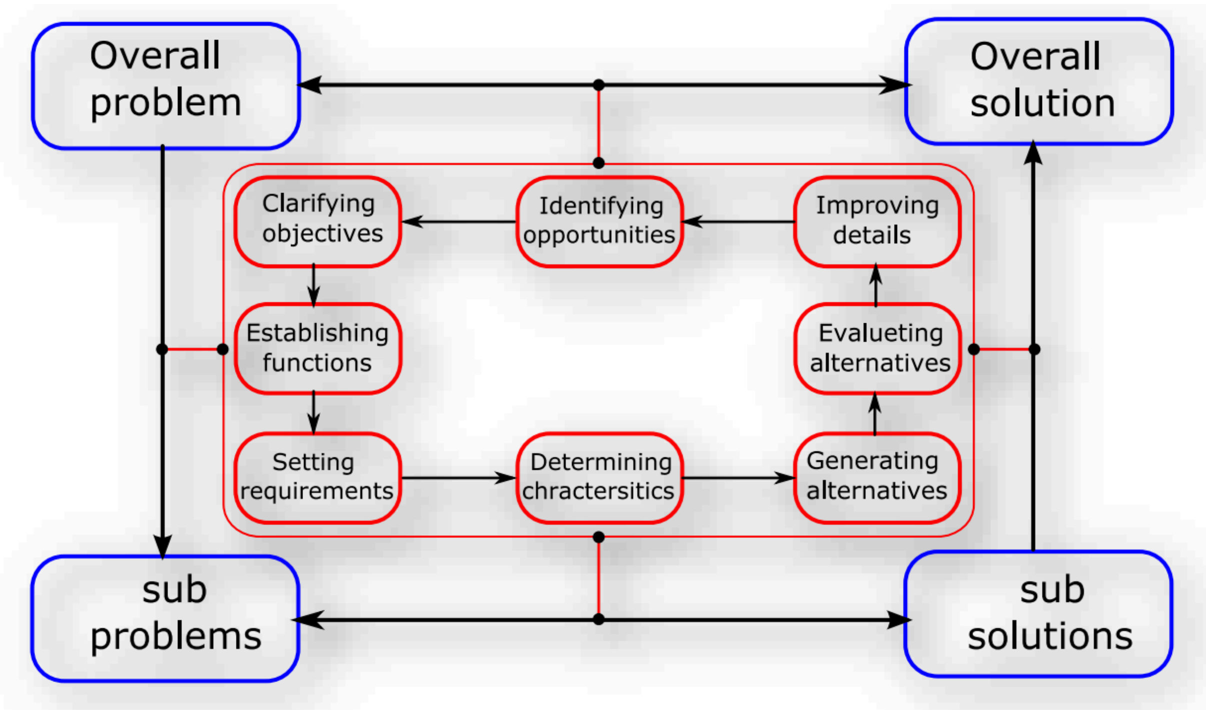

Figure 6:The Nigel Cross design method (Cross, 2008)

2.2 Clarifying Objectives

When starting on a problem, the designer rarely has all the information needed to create a product which satisfies all the aspects. This stage of the process tries to create clear objectives for the project by breaking them down into sections and sorting by importance. Based on the conversations with Laerdal, I've been able to create an objective tree highlighting the objectives of the problem (see Figure 7).

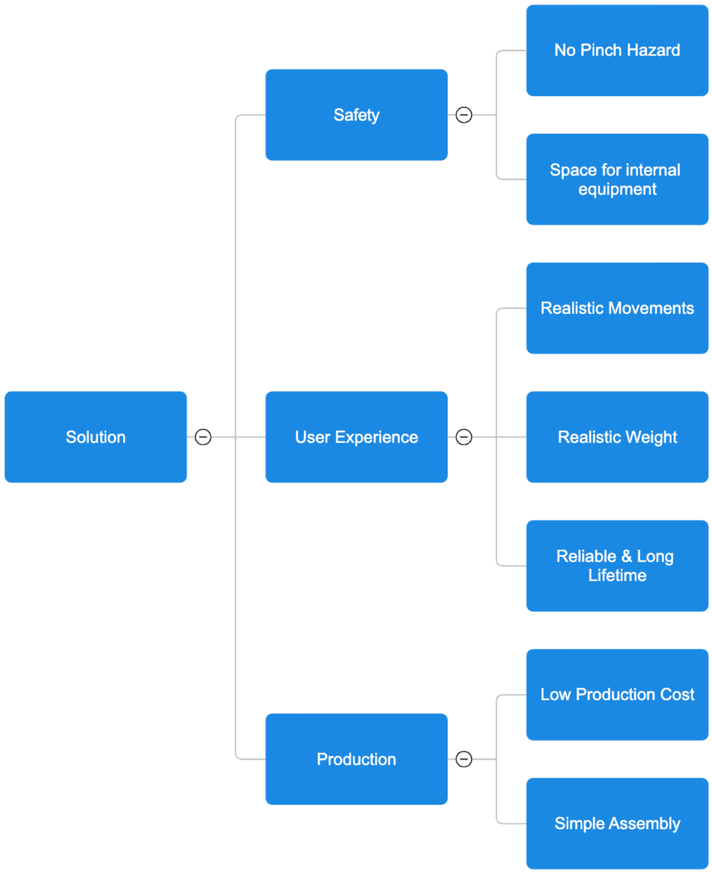

Figure 7: Objective tree

2.3 Establishing Functions

The function of the shoulder joint is essentially to mimic a relaxed human shoulder joint in the way it moves. Although most of its use is stationary in bed, the joint needs to be able to support given loads for different training scenarios. In both cases the movement should feel natural and realistic for the user. The user should be able to handle it roughly without fear of breaking the equipment as it will be used for a variety of training situations. The movement is described in chapter 1.2.3.

2.4 Setting Requirements

This part has already been covered in the introduction, see chapter 1.4 Requirement Specifications.

2.5 Determining Characteristics

Creating new products comes with working across many different fields with very different interests for the product. When determining the project characteristics, it is important to keep in mind both the engineering characteristics and customer characteristics. The Quality function deployment method (QFD) is a useful tool in this scenario. The aim of the QFD-method is to find a balance in customer and engineering characteristics using the house of quality matrix (HOQ) (Cross, 2008).

The HOQ-matrix, shown in Figure 9 below, correlates customer needs with engineering characteristics. Each row represents a customer requirement, and each column represents a design characteristic or feature. By analyzing the interrelationship between these, the HOQ-matrix can help in prioritizing design decisions and make sure that product development efforts are aligned with customer expectations.

The “roof” on top is the correlation matrix where design characteristics which affect each other positively or negatively are denoted with “+” or “-“ respectively. In the bottom right is the main house which correlates the design characteristics with the costumer characteristics and is given a value based on how much they affect each other (See Figure 8). The customer characteristics are ranked by importance which is calculated with the values in the main house which gives us the final importance rating. See Figure 9 below for the HOQ for the shoulder joint.

◉	Strong	9
○	Medium	3
△	Weak	1
	No assignment	0

Figure 8: Symbol Values

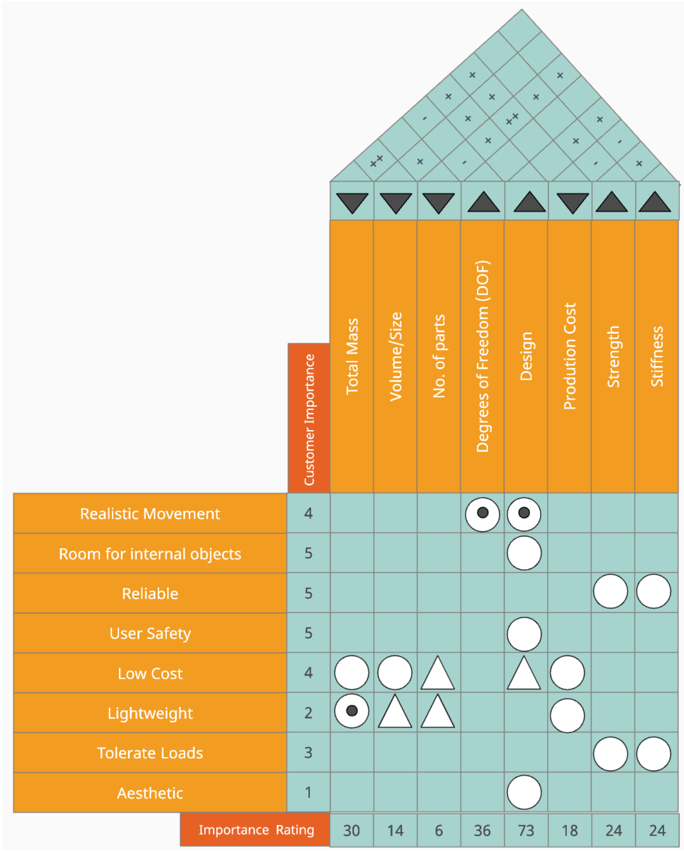

Figure 9: HOQ - Shoulder Joint

From Figure 9 it is shown that design choices are rated highest as there are many factors that are reliant on it. DOF is rated second as this is important to the goal of creating a realistic product. Based on the HOQ it is determined that the focus for the project should be the design and DOF.

2.6 Generating and Evaluating Alternatives

Perhaps one of the most important parts when doing concept development is generating different alternatives. In product development there are several methods developed for designers to utilize when generating ideas. In accordance with the methodology chosen, the thesis is going to use a combination of the Morphological chart and the Weighted Objective method.

2.6.1 Generating Alternatives

For generating alternatives, the Nigel Cross method utilizes the Morphological chart (Cross, 2008). This is a method that improves with the number of sub-problems and complexity. The morphological chart strikes a balance between creativity and structure that helps the user expand on their ideas in a systematical manner. By breaking the problem down into several sub-problems, the user is assisted in creating a better understanding. After breaking it down enough, the user must come up with a variety of different solutions to all the different sub-problems. Finally, the user combines the different sub-solutions, illustrated by color-codes, and will end up with a variety of different solutions that are evaluated in the next chapter. See Table 2 below for the morphological chart for this project.

	1	**2**	**3**	**4**
Structure	Exoskeleton	Endoskeleton	Combination	
No. of Parts	One	Two	Three	Four
Joint Type	Ball	Pin	Hinge	Cylindrical
Shape	Cylindrical	Circular	Combination	Square
Coupling	Nuts	Clip-on	Male/Female	

Table 2: Morphological Chart

2.6.2 Evaluating Alternatives

For evaluating the generated alternatives, I have used the weighted objective method. Based on the criteria made previously and the alternatives from the morphological chart. This tool is used to avoid bias and to compare the ideas in a systematic approach. I rank the color-coded combination by previously determined factors important to the product and choose the solution to go for from there. See Table 3 below for the weighted objective method.

Objectives	Design	Degrees	Internal Space	Size	Sum
Blue	0	1	0	1	2
Red	1	1	1	1	**4**
Green	1	0	0	1	2

Table 3: Weighted Objective Method

As shown in Table 3, the red concept combination scored highest and will be the basis for the design process.

2.7 Improving Details

The final step in the design method is about evaluating the parts used in the construction and look for ways to reduce the cost without reducing the value. This is done by listing the components and determining the value as perceived by a customer. Here ranked from 1-5 based on importance. See Table 4 below.

Part	Function	Customer Value	Comments	Revision
1x Body	Connect shoulder to main body and extension/flexion	4	Important part. Design should enclose for pinch hazards but reduce materials where possible.	Cover arm-part during rotation. Remove unnecessary volume.
1x Pin	Connect main shoulder parts	2	Allows for great freedom in rotation for the arm. Supports structure.	Consider mechanisms for connection/assembly that is part of the pin
1x Arm	Connect shoulder to arm and adduction and internal rotation	4	Need to be strong and stable.	Move enclosure around to guide the movement and avoid pinch. Make coupling point part of the arm. Avoid excessive “branches” from the part.

Table 4: Improving Details

3 Material Selection

The material selection process will be done using CES Granta Edupack combined with methods from Ashby's Material Selection in Mechanical Design (Ashby, 2016).

The force acting on the shoulder in the case study is an axial load from the pulling of the arm.

Constraints: not fail by yielding or fast fracture.
Goal: minimize mass.
Free variables: Choice of material and wall thickness.

Maximizing the material index $M = \frac{E^{\frac{1}{3}}}{\rho}$ will find the materials most suited. By limiting the y-axis, the materials chosen show the most toughness and yield strength at the lowest density, this illustrated in Figure 10 below. The functional temperature from Table 1 was also accounted for in the limit stage beforehand.

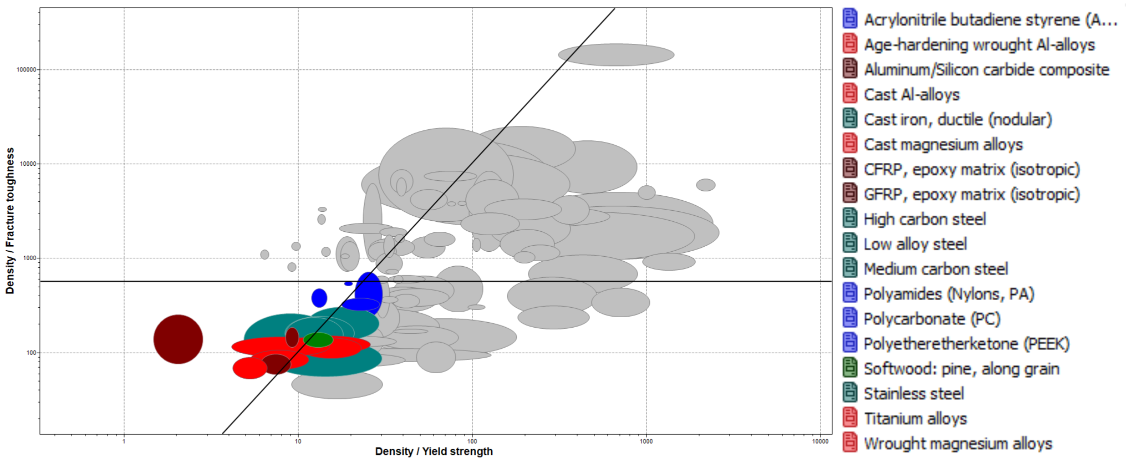

Figure 10: Granta Edupack Step 1

Then to eliminate more options it can be sorted by density and price to find the most suitable candidate. See Figure 11 below. Here are the remaining materials sorted by price and density, the left corner being the lowest value for both and increasing in y and x direction.

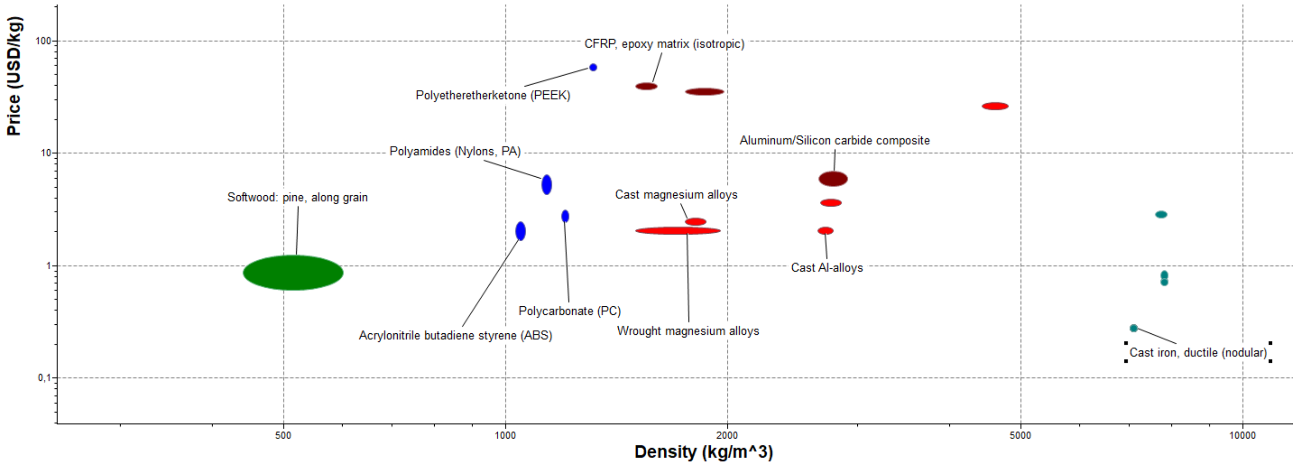

Figure 11: Granta Edupack Step 2

The results in Figure 11 show that polycarbonate, polyamides and acrylonitrile butadiene styrene (ABS) are the most promising polymers regarding price and density. For alloys it shows cast magnesium alloys and wrought magnesium alloys to be the most promising. All the polymers are indeed suitable candidates for the part as they all fit the criteria and on top are good for molding. For the numerical analysis ABS will be utilized as it scored best in Granta Edupack. ABS have a low weather resistance as UV-rays can discolor and make it more brittle, but as it will be incased by silicone from the skin on the patient-simulator it will be protected (Epsotech, 2024). See Figure 12 below for the mechanical properties for ABS used in the numerical analysis.

Elongation at Break	10 - 50 %
Elongation at Yield	1.7 - 6 %
Flexibility (Flexural Modulus)	1.6 - 2.4 GPa
Hardness Shore D	100
Stiffness (Flexural Modulus)	1.6 - 2.4 GPa
Strength at Break (Tensile)	29.8 - 43 MPa
Strength at Yield (Tensile)	29.6 - 48 MPa
Toughness (Notched Izod Impact at Room Temperature)	200 - 215 J/m
Toughness at Low Temperature (Notched Izod Impact at Low Temperature)	20 - 160 J/m
Young Modulus	1.79 - 3.2 GPa

*Figure 12: ABS Properties (*Omnexus, n.d.*)*

4 Analysis

This chapter covers the analytical and numerical analysis of the product. The analysis part is simplified due to the nature of the thesis being concept oriented. The analysis will only consider the arm part and assumes it a hollow pipe structure. This will be discussed in chapter 6.2. The analysis is based on the case study presented in chapter 1.3.

The case study shows a patient being dragged to safety by the arm. This results in tension in the shoulder on the patient. Assuming a hollow pipe, the tensile stress in the arm during the case study is given by:

$$\sigma = \frac{F}{A} = \frac{F}{\frac{\pi(d_o^2 - d_i^2)}{4}} = \frac{4F}{\pi(d_o^2 - d_i^2)} = 4.67MPa$$

where σ is tensile stress, F is the axial load defined in the case study, A is cross-section, d_o and d_i is outer and inner diameter respectively (Appendix A).

There are not expected to be any major deflections due to the low axial load, and no other forces acting on it. This will be shown in the numerical analysis.

The numerical analysis is done as an assembly in Solidworks. The parts were positioned like they would in the case study assuming the patient's arm was lifted by abduction. After positioning the parts accordingly they were applied the material determined in the previous chapter, and put constraints and loads on to simulate the case study as seen in Figure 13 below. The part connected to the upper body (shown to the right in Figure 13) are fixed to the upper body frame allowing no translation on any axis. The orange arrow in the center is the visual for gravity acting on the construction. To the left are pink arrows which are the tension force from dragging the arm.

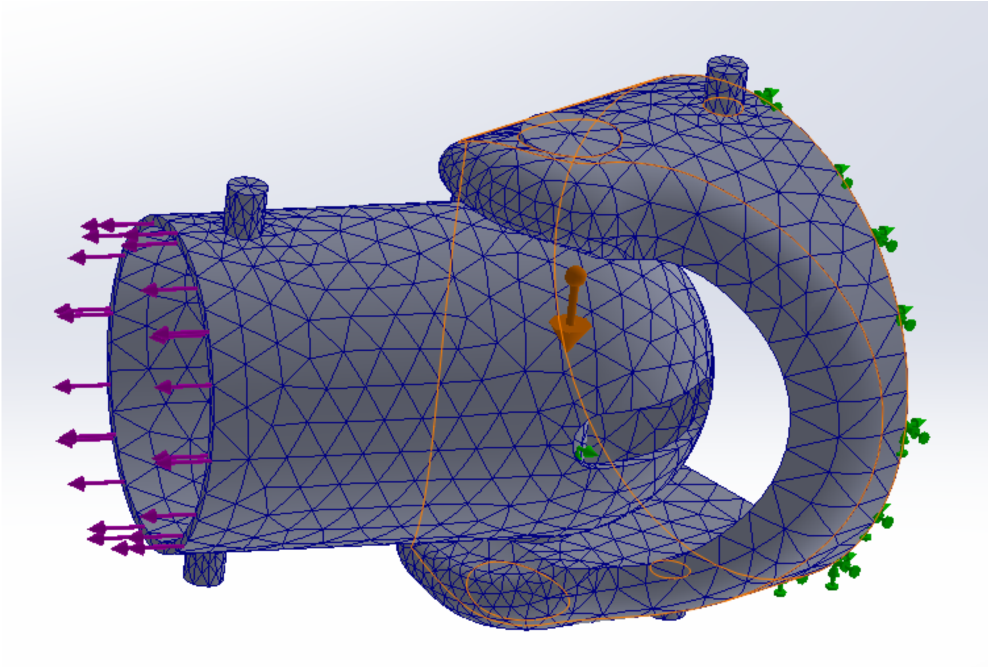

Figure 13: Simulation Case Study

The construction is fully meshed in Figure 13 and is visibly coarse on most areas, but concentrated in areas of steep angels, fillets and couplings. See Figure 14 below on the left for the mesh details. Figure 15 below shows all the configurations for the static analysis. As there were some problems with simulations, the pin was removed from the assembly and there was instead added a pin connection between the arm and the base. The fixed hinge solution was also used for the same effect. Using the pin in the assembly resulted in an error message which only got resolved by not using it and instead applying a pin fixture.

Mesh Details

Study name	Static 1* (-Default-)
DetailsMesh type	Solid Mesh
Mesher Used	Blended curvature-based mesh
Jacobian points for High quality mesh	16 points
Max Element Size	0,00794355 m
Min Element Size	0,00264782 m
Mesh quality	High
Total nodes	12647
Total elements	6722
Maximum Aspect Ratio	9,9923
Percentage of elements with Aspect Ratio < 3	77,2
Percentage of elements with Aspect Ratio > 10	0
Percentage of distorted elements	0
Number of distorted elements	0
Remesh failed parts independently	Off
Time to complete mesh(hh:mm:ss)	00:00:08
Computer name	

Figure 14: Mesh Details

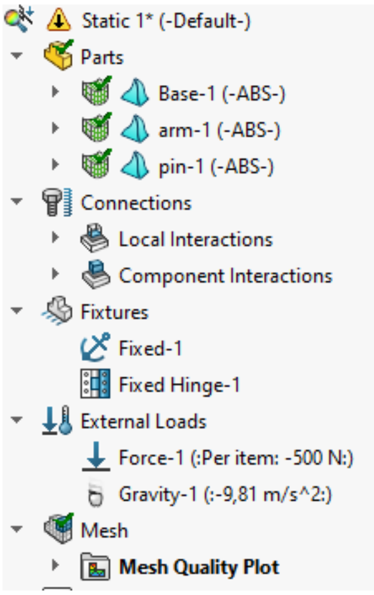

Figure 15: Static Analysis

5 Results

5.1 Concept

The concept developed ended up being a three-part assembly that consists of a base which connects to the main body of the patient, a hollow arm which connects to the rest of the arm and a pin joint that connects the two and allows for abduction. The base and arm have two pins sticking out of the body which is the male part of a connection that guides the rotation of the two. The female part is responsible for guiding the rotation for the number of degrees it is supposed to have for flexion/extension and internal/external rotation. However, the abduction/adduction movement is installed in the concept. The pin joint fastened to the base allows the arm to rotate from approximately 0 degrees up to approximately 140 degrees which almost fulfills the ideal requirement, but exceeds the minimum set by Laerdal. The arm is hollow and has a slit on top which is accessible for tubes all throughout the flexion-movement. The slit is approximately 10x30mm which can fit the three cables of 5mm diameter each. The concept is within the maximum volume from the requirement. Figure 16 below shows the final concept based on the methodology used in chapter 2. See Figure 17 for exploded view.

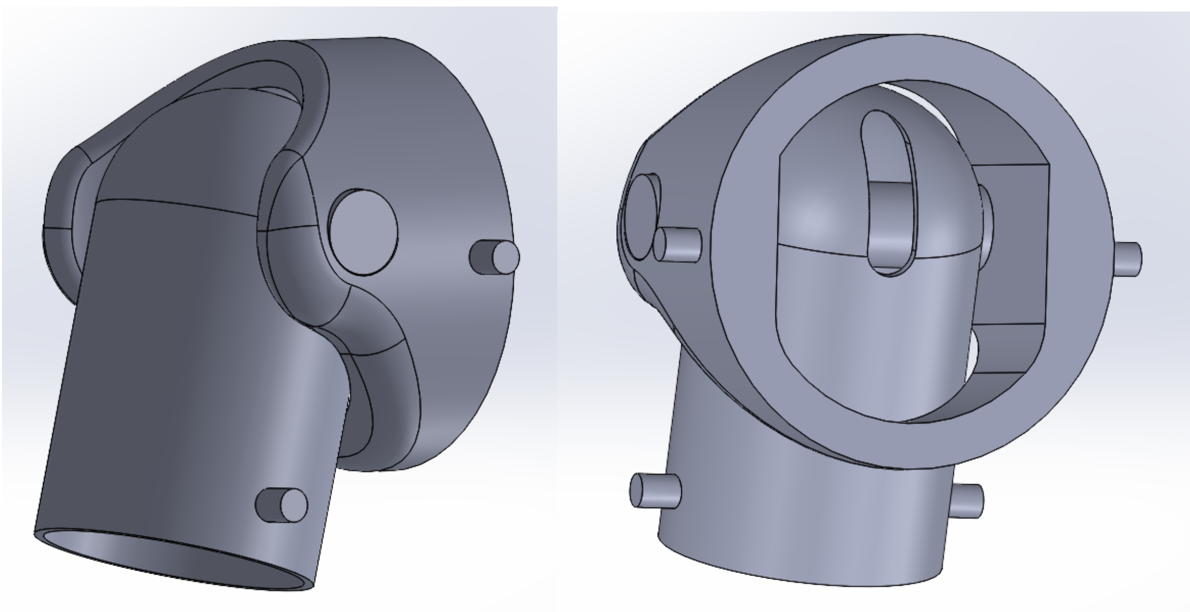

Figure 16: Final Concept

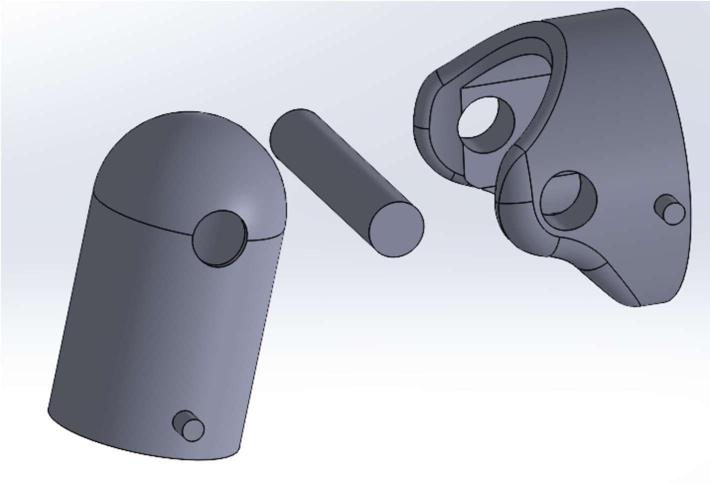

Figure 17: Exploded View

5.2 Analysis

After applying all the loads and constraints, the simulation is run, and below are the resulting von Mises-stress and displacement (shown in Figure 18 and 19 respectively). The resulting stress shown to be around 3MPa, except for one point on the top of the opening in the arm, which is 10.8MPa. The base seems to show zero stresses and not affected by the simulation. The displacement is like the stress not affecting the base, and the maximum displacement is shown as 0.39mm at the bottom of the arm where the load was placed.

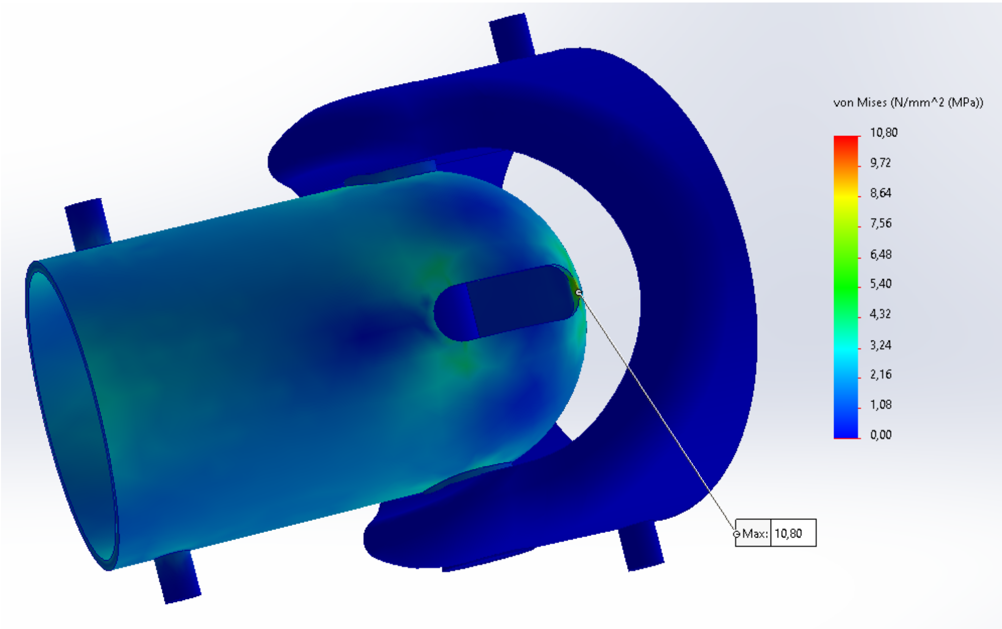

Figure 18: Von Mises-stress

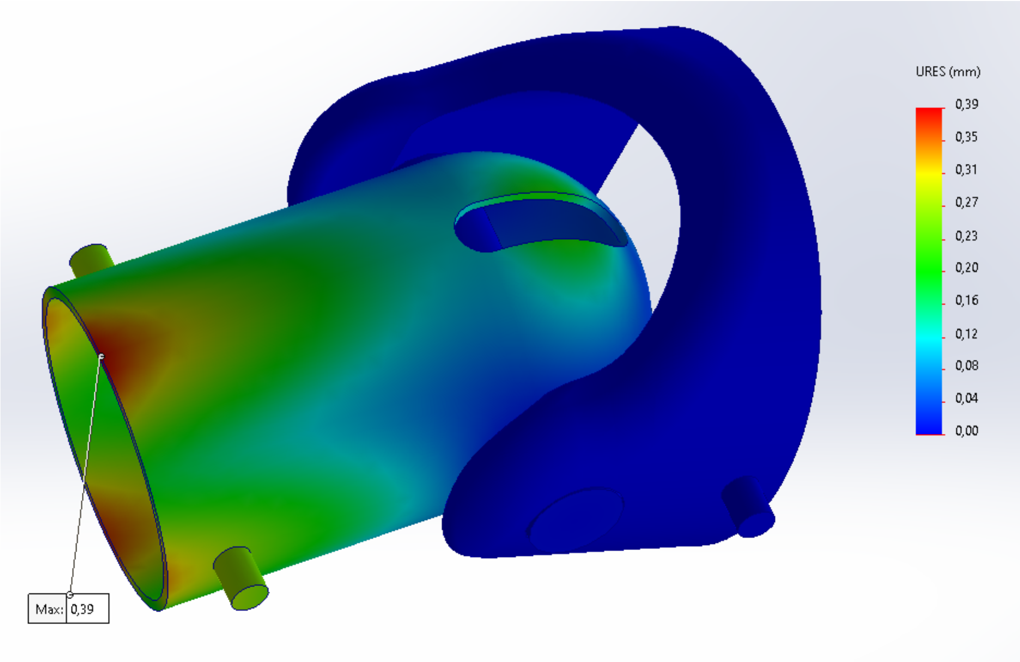

Figure 19: Displacement

6 Discussion

6.1 Concept

The process of creating concepts is usually thought of as a mostly creative action, but in reality it requires both a plan and a vision to achieve a good result alongside a systematic approach to the work. The final concept was developed using both; The systematic approach from the Nigel Cross method and the creative parts from myself.

The pin joint was originally meant to serve a purpose other than a visual, but the simulations showed constant error messages about excessive displacement regardless of the change in design or options. In retrospect it was most probably too few fixtures on the assembly for it to resist the load. The fixtures should have been placed, in addition to the back of the base and the pin joint, on the male pins on both the base and the arm. Unfortunately, it was discovered too late for more attempts.

The pin joint ended up only being a guide for the arm in the simulation, but for the concept the options for using it are plenty depending on the needs. It still serves as a solid part in connecting the other two parts, and the degrees of flexion/extension is only limited by the surrounding construction. Connecting the pin join onto the construction can be solved in many ways. It can be solved with a nut and bolt if it has to be more secure, or by using clip-on mechanism to avoid more volume around the parts etc.

Solving the DOF-requirements was done by creating structures around the parts to limit the movement on collision. Using an exoskeleton comes with the idea of freeing up more space for the internal rooms of the patient-simulator, so keeping the rotational parts outside continues the same idea. It does however come with additional problems to solve. The outer layer on top of the skeleton is the skin which in this case is made of silicone. This would require female parts connecting to the shoulder to be covered to avoid coming in contact with the skin. The male design is also more prone to fractures due to the acute angels which can be adjusted with a fillet around the base.

The safety standard IEC62368-1 was mentioned in chapter 1.2, and prefaces that pinch hazard is of importance for being allowed to sell in the EU market. The design took this into consideration and closed the gaps around the arm such that even in abductional rotation, there would not be room for fingers to slip inside from top. As there is a layer silicone on top as well, it should not be possible to get pinched inside the mechanism from the top. However, the bottom side becomes exposed when in an abducted position. Here there is a gap of approximately 15-20mm that could potentially cause harm. The silicone skin will resist and protect somewhat if the collision happens slowly, but not enough if the abducted goes back to adducted position at a higher speed.

6.2 Analysis

The analysis was simplified due to complexities in geometry of the base and due to problems with the simulation. As mentioned in chapter 6.1 the solution to the simulation problems might have been figured out, but due to a lack of time it was too late to try again.

There should have been done experimental tests outside to determine values which are extremely difficult to obtain from calculations as the outside isn't linear in any sense. The resulting stresses from the simulation was on average not far off the analytical calculations, but the maximum stress in the top part of the arm exceeds it by almost a factor of 2.5. This seems to be correlated to the simulation errors of not being able to include all the parts from the assembly in the simulation. The point of maximum stress is unrealistic as the load comes from the opposite pole and is supposed to meet resistance in the pin joint, but since it is instead met with a replicated fixture-pin the stress seems to be a bit misplaced.

The displacement results from the simulation show promise by having a maximum value of 0.39mm on the bottom edge. The displacement around the pin joint show close to 0.00mm, which again seem to be related to the attempt to replicate the pin in the simulation as it would meet a reaction force here.

If the male couplings on the base and arm would act as intended in the simulation, the forces would be maximized here. ABS would still be a suitable material as it doesn't yield until, and the forces are not enormous. It could be that the stresses on the male (and female) couplings would reach values such that the factor of safety (FOS) would be too low to call reliable or even bigger than the yield strength of ABS. It might be a suitable solution to use one of the alloys found in Granta Edupack for the male-female couplings to ensure no failure by yield. For example, the wrought magnesium alloys have a range of different variants, and some have yield strengths of 300MPa and above (You, 2017).

6.3 Further Work

If the concept were to be further developed these are my suggestions for things to do:

- Do a practical experiment of the case study and measure the forces acting on the joint with sensors and find a mean drag coefficient for rough terrains like the woods.
- Adjust the design such that the gap between the base and arm is small enough so that there is no pinch hazard while keeping the abduction/adduction-rotation at the same degrees.
- Run more simulations on the joint with accurately placed fixtures and loads for different variations coupling mechanisms. Get more data on the male-female coupling strength needed to avoid yield and fracture.
- Test different ways to connect the pin joint, and to connect the base to the body without hindering rotation.

7 Conclusion

The goal for the thesis was to explore different concepts for a shoulder joint and move forward with a chosen concept using the methodology learnt during the master's program. The thesis goes through a methodical and systematic approach to creating a concept for a shoulder joint. Using the Nigel Cross method the shoulder slowly takes form after analyzing function, customer wants and product requirements. The main factor for function was to create a realistic movement that satisfies all three DOF. The final concept has succeeded in creating a realistic abduction/adduction that satisfies the minimum requirements and has created a solution that allows the other two movements to be satisfied. The analytical results come with an asterisk as problems occurred, but showed somewhat expected results in the arm.

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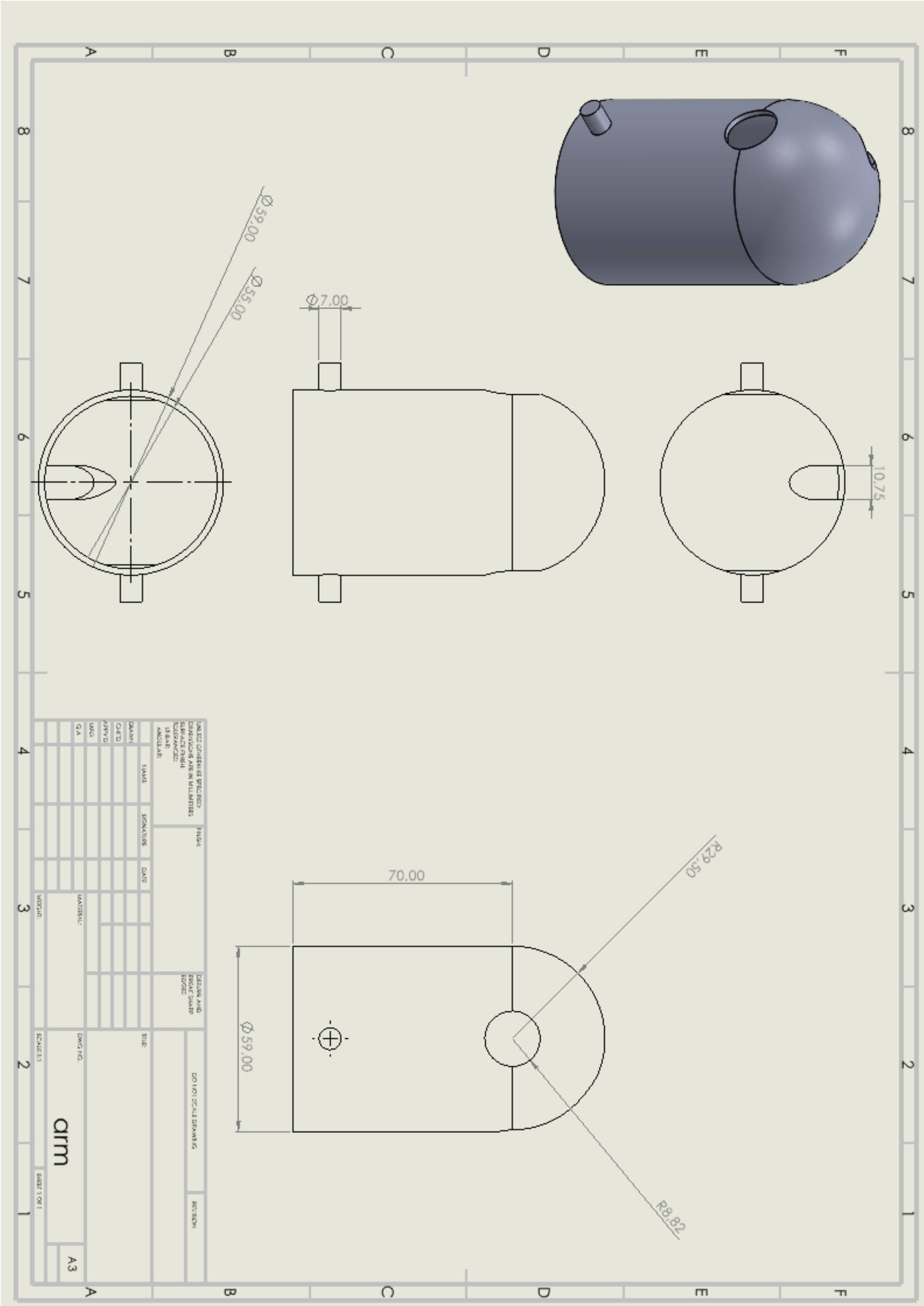
Appendix A



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Ø7.00
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70.00
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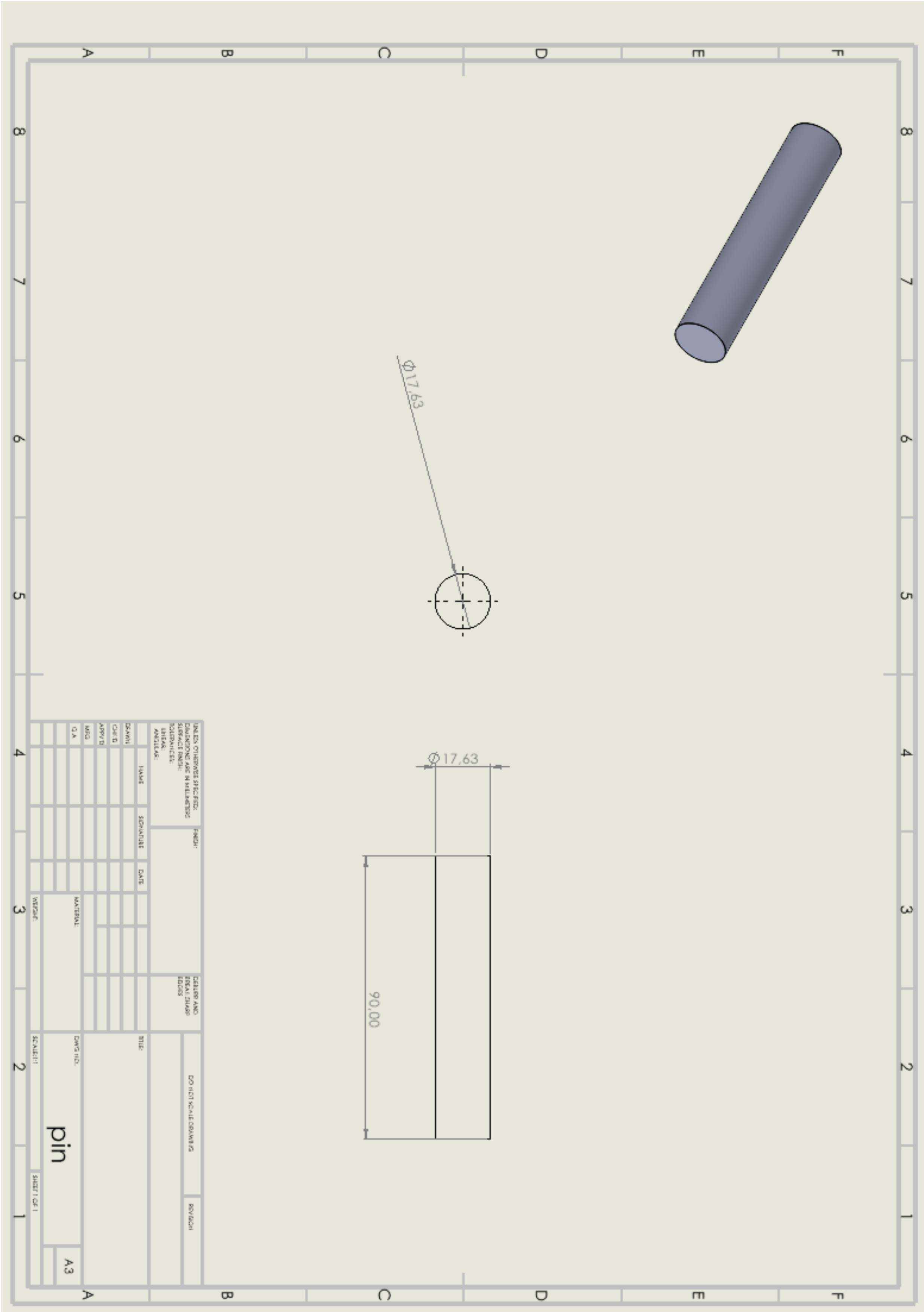
A3
DO NOT SCALE DRAWING

Appendix B



Appendix C