UNIVERSITY OF TWENTE.

Hankamp Rehab

Innovatie in revalidatie

Redesign of the MASMini

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Biomechanical Engineering MSc Internship Report

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1 Preface

Part of the mechanical master program is the internship, which gives you the chance to work in a company for a few months. When I was looking for internships I wanted something related to the field of rehabilitation without forgetting about the mechanical background, and Hankamp Rehab was offering that. It is located in Enschede, The Netherlands, and it has a close research involved relation with the University of Twente. Therefore, they are used to work with students. The internship lasted three months, from the 4th of September until the 30th of November. The working hours were between 8:30 and 17:00, with a lunch break included, from Monday to Friday. I worked under the supervision of Claudia Haarman.

The topic of this internship is the redesign of a gravity arm support, more exactly, the MASMini from Saebo produced in Hankamp Rehab. The main purpose is to make it cheaper, whether looking at the production methods or to the specific design of pieces.

During this period of time I learned how the gravity compensation works and how it is applied to a functioning device. With some literature research and reading of previous assignments (the internship report from Bart Schulten and the PhD dissertation from A.G. Dunning), the design process started. Beginning with some pre-concepts, a detailed concept has been designed in SolidWorks and finally I have been able to 3D print some pieces to test the principle of the mechanism.

Finally, I would like to thank my supervisor Claudia Haarman for her continuous guidance and her time offered to help. I also want to thank Koen Heuver for his practical advices during the development of the mechanism, whose experience has been very useful for the decisions making. And finally, I would like to mention and with that thank the rest of the team at Hankamp Rehab.

2 Summary

This report provides the main steps followed and the results obtained at the redesign of the mechanism of an arm support developed during this internship. The internship has been done at the company Hankamp Rehab, in Enschede, The Netherlands.

First, some existing gravity arm supports have been observed and their characteristics have been compared with the actual MASMini from Saebo. From that, the goals of the assignment have been set and the requirements for the new design have been defined. The main objective is to make the MASMini cheaper so patients can afford it and use it as a home arm gravity support.

Second, a morphological map has been done and from there six pre-concepts have been obtained. With the use of the weighting factors in the requirements, two concepts have been selected and further developed. Taking into account the advantages and disadvantages each one provided, one concept has been chosen and described in detail, which will lead to the final mechanism.

Finally, some force simulations have been made by means of SolidWorks and the (re)designed pieces have been 3D printed in order to test the proposed mechanism.

Additionally, a BOM list has been made showing the expected prices of the assembly parts in order to see the final price and compare it. With this, it can be concluded if the initial objective has been achieved.

Contents

3 Table of symbols and definitions

Symbol	**Name**
DOF	Degrees of freedom
ROM	Range of motion
ADL	Activities of daily living
BOM	Bill of materials

4 Introduction

As life expectancy increases, medical resources have a greater demand coming from the elderly sector of the population. Health care systems have to provide more medicines or rehabilitation programs for strengthening weak muscles.

In the rehabilitation sector, patients with different neurological or physical disabilities are treated in order to improve the strength, the motor control or to enable them to be more independent.

Nowadays, stroke is a common disease worldwide, affecting mostly people over 65 [8], where part of the brain cells are damaged or die. This leads to a loss of physical functions and therefore, the brain has to learn again the damaged or lost skills. Stroke can affect the upper limb such as shoulder, elbow, wrist and hand. Early and constant rehabilitation is encouraged to recover those physical functions again, and it can also teach new ways of doing things to compensate the lack of abilities. It is a continuous process where it does not end at the hospital but should be followed at home.

These are involved in activities of daily living (ADL), such as eating or writing. Therefore supportive devices which can be placed at home, in addition to the recommended rehabilitation, make the patient's life easier and in one way or another possible to achieve usual daily tasks.

4.1 Background

[5] It has been seen that the ROM for ADL is less than the normal anatomic ROM. In other words, for functional activities less ROM than what a healthy body can do is required.
Some of the comparative results can be seen in the following figure 1.

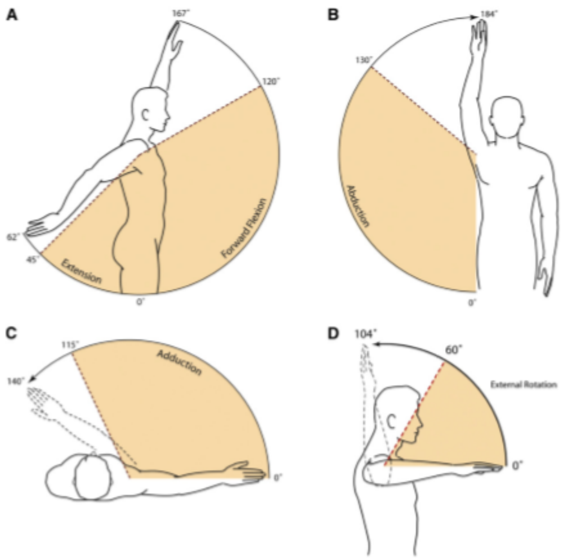


Figure 1: Functional ROM (yellow) compared to the anatomic ROM

4.2 Overview of existing arm supports

There have been developed several medical devices intended to help patients with the treatment of proximal weakness. A brief review is done:

- **Armon Edero**: fully mechanical, adjustment of mass compensation with a spindle. Horizontal ROM bigger than the vertical ROM.[1]
- **Armon Pura**: electronical weight adjustment. Vertical ROM bigger than the horizontal ROM.[2]
- **WREX**: linear elastic elements (adjustable number of rubber bands) to compensate the effects of gravity. Use of a parallelogram as a first link.[6]
- **Top/help**: rubber band mass compensation adjustment, use of a parallelogram as a first link.[4]
- **Dowing**: manually adjustable gravity compensation with a rotational button, spring balancing.[3]

4.3 Hankamp Rehab

Hankamp Rehab is the sister company of Hankamp Gears, a gear manufacturer located in Enschede, The Netherlands. Since 2009, Hankamp, in connection with the University of Twente, seeing the demanding rehabilitation market, started a rehab start up group which develops, produces, sells and distributes rehabilitation products from the upper limb (Saebo Globe for example) to the lower limb (ZeroG gait and balance system). They have several partners, which are Saebo, Aretech, RehaCom, Tyromotion and APDM.

4.4 Saebo MASMini

For this internship the Saebo MASMini, developed and produced in Hankamp Rehab, has been studied and partly redesigned.

The Saebo MASMini(figure 2) is a zero gravity dynamic arm support, a smaller and lighter version of the Saebo MAS(figure 3) whose ROM is bigger. It is designed for patients with shoulder and elbow weakness, and facilitates and supports the upper extremity. The zero gravity feature counteracts the effect of the arm gravity, making it 'weightless' and enabling the patient to move the arm which otherwise would not have been possible. [7].

Figure 2: Saebo MAS Mini

Figure 3: Saebo MAS

The principle behind it is an adjustable spring based parallelogram (see figure 4). It is possible to compensate the device from patient to patient, in other words, depending on each user's arm's weight. Once it is compensated, the product will be in equilibrium for any configuration. Because the MASMini allows movements in all planes, any activity is restricted and offers an extense ROM.

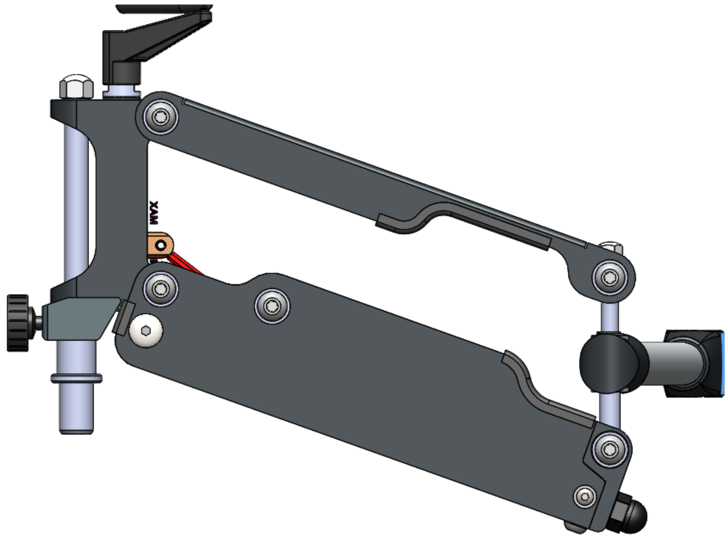


Figure 4: Parallelogram of the MASMini

4.5 Goal

The main goal of the assignment is to make the MASMini cheaper than it is now so more patients can afford it and use it as a supportive device at home.

This main goal can be divided in more specific tasks:

- Analise the different mechanisms for a gravity compensation arm support.
- Obtain the minimum forces to adjust the mass compensation.
- Reduce the number of parts.
- Make a simple assembly based design.
- Take into consideration the safety of the user when designing.
- Create a (3D printed) prototype to test the mechanism.

5 Analysis

At the beginning of this section the requirements of the product are set up. A morphological map follows where several functions and ideas are proposed in order to meet those requirements. From that, 6 pre-concepts are obtained and briefly described, giving a general idea of what they could become. Finally a small reflexion is given arguing which pre-concepts have a real potential.

5.1 Requirements

1. Use requirements:
   a. The product should be able to support up to 4kg or more.
   b. The product should be used by people with arm muscle weakness.
   c. The range of height should be at least 300mm.
   d. There must be at least 3 DoF.
   e. The connection between the links should maintain vertical.
   f. The overall product should be around 200 €.
   g. Forces the user has to exert when pushing a button with one hand fingers should be less than 3 kg.
   h. Forces the user has to extent when pushing/pulling an object should be less than 10 kg.
2. Safety requirements:
   a. The product should not harm the user.
   b. The product should be certified for a home use.
3. Ergonomics requirements:
   a. The product should be intuitive to attach to the forearm.
4. Use wishes:
   a. It must be possible to control the product easily after reading the instructions without any prior knowledge.
   b. The assembly must consist of a minimum number of (different) components.
   c. The product should use standard purchasing parts wherever possible.

5.2 Morphological map

See table 8 in section 11, Appendix B.

5.3 Pre-concepts

1. **Counterweight (see figure 5):**
   The top side of the vertical bar connecting to the table is connected to a horizontal bar. This last bar will carry the counterweight mass on one side and on the other side is connected to a third bar which provides 2 additional DOF. There is the possibility to clamp the third bar for reasons of security.
   There is a torsion spring in the connection of the vertical and counterweight bar, which can be adjusted by means of a spindle.
   The forearm support will be made of an elastic material, to be able to have unique size

design. A velcro will adjust the support to the forearm.
The table mount is a press mount and the heigh adjustment of the vertical bar can be done with a lever.

2. **Triangular (see figure 6):**
Two triangle frames are connected to each other by a bearing and two springs at the furthest corners. One of the springs tension will be adjustable in different levels by means of a string connected to a rotating knob. There is a bar linked to the upper triangle adding 2 DOF, and for security it is possible to clamp the bar.
The forearm support will be made of an elastic material, to be able to have unique size design. A velcro will adjust the support to the forearm.
The table mount is clipped to the table and the height is adjusted with a lever and pressuring (like a bike seat).

3. **Rolling guide (see figure 7):**
There is a spring connected to a rolling guide which goes upwards and that defines the ROM.
The forearm support is one long elastic piece that is almost closed and can be adjusted with velcro stripes.
The table mount is a press mount and the height adjustment is done by pressuring a screw to the bar.

4. **Peaucellier (see figure 8):**
The linkage connection is based on the Peucellier mechanism, which consists of two rhombus where each pair of bars have the same length. The tension will be produced by rubber bands acting as springs. An extra bar will connect the mechanism to the forearm support, giving an additional DOF. For security, it is possible to clamp this last bar to the main linkage and when unloading the spring tension by means of a button will be possible to go quickly to the lower level.
The forearm support is made of elastic material easier to adapt to the user, it will have something stronger to hold the position.
The base is fixed to the table with a clip mechanism.

5. **Chebyshev (see figure 9):**
The linkage connection is based on the Chebyshev mechanism composed of three bars and providing a straight line motion. The spring-string-pulley mechanism is connected in one of the crossed bars and a button/clip on one bar will allow the distance adjustment. A second bar is linked to obtain an additional DOF. This last can be secured with a clamp.
The forearm support includes an elbow support, adjusted with a velcro and it can be moved backwards and forwards for a more fitted adjustment.
The table mount is a standard mount that can fit a squared piece already fixed to a table/wheelchair. It can be adjusted with a screw, same as the height.

6. **Gas spring (see figure 10):**
The mass compensation is a counterweight placed on a horizontal bar. This bar has a gas spring mechanism connected to the vertical bar. The same horizontal bar will be connected to a third bar which will provide 2 additional DOF and it can be secured with a clamp.
The forearm support includes an elbow support adjusted with a velcro and on the front it has a thumb glove for an easiness of placing the arm correctly.
The base is fixed to the table with a clip mechanism.

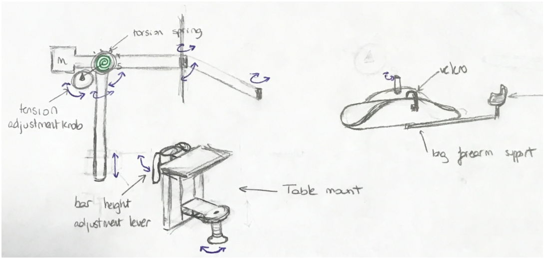


Figure 5: Counterweight

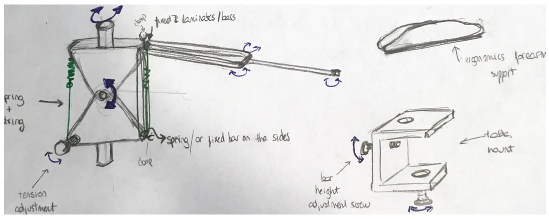


Figure 6: Triangular

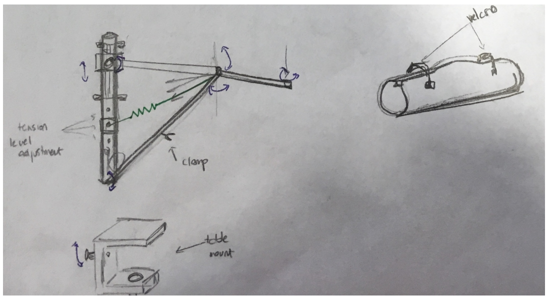


Figure 7: Rolling guide

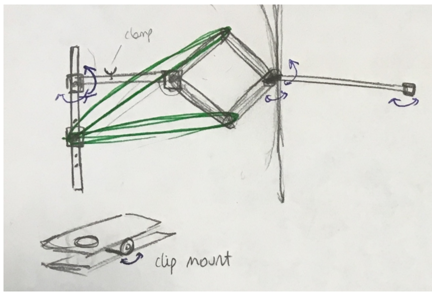


Figure 8: Peaucellier

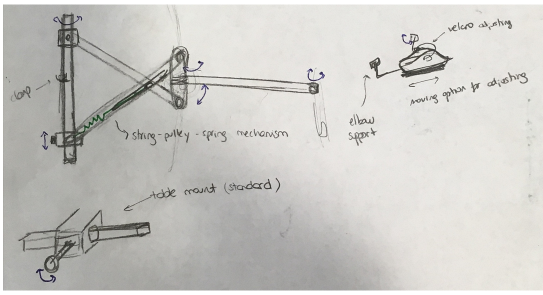


Figure 9: Chebyshev

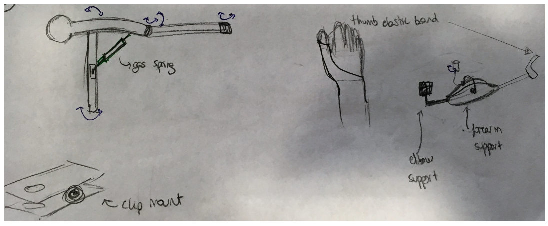


Figure 10: Gas spring

5.4 Results

After taking a look to the morphological map and defining six pre-concepts, some drawings have been made to see more clearly their functionality. See figures from 5 to 10.
In order to grade their functionality, some general requirements that can be judge at this point of the design phase have been taken into account. For that, a weighting factor from 1 to 3, being 3 highly fulfilled and 1 not, has been given to each pre-concept to evaluate it. The grading and results of the weighting factors can be seen in the table 1.

		Requirements					
		1b	1d	1e	2a	3a	Total score
Pre-concepts	1.- Counterweight	3	2	1	3	2	11
	2.- Triangular	3	1	1	2	2	9
	3.- Rolling guide	3	3	3	3	2	14
	4.- Peaucellier	3	3	1	3	2	12
	5.- Chebyshev	3	3	1	3	2	12
	6.- Gas spring	3	2	1	1	3	10

Table 1: Weighting factors of the pre-concepts

The highest score is for the rolling guide pre-concept, and since it is the only one fulfilling all the requirements (see 1e requirement column at table 1), the rest of pre-concepts have been discarded.

One pre-concept is not enough, to go to the next design phase more are needed to analyse their functionality and to be able to compare them. Therefore, from this pre-concept two variations have been formulated. The mechanism principle is the same, but the main difference is the placement of the pulley spring system and the connection of it to the additional linked bars. A small analysis/reflection of both ideas is made before continuing with the more detailed concept phase.

5.4.1 Concept 1

For a visual representation of the concepts see the figures 11 and 14, developed at section 6.

1. **Functionality**
   The external mass is connected to a linear guide by three serial bars linked by bearings between them, so the turning around the vertical axis is enabled. This linear guide, which allows a total up and down movement of 300mm, is located on the outside of a vertical tube. At the same time the guide is connected to the pulley spring system with two intermediate bars.
2. **Spring-pulley system**
   The spring is fixed on one side to the end of the hollow tube. The first has to be connected to the first linked bar, which is done by means of a cable and a pulley. The pulley is also located inside the hollow tube.
   For the mass compensation, one distance related to the spring pulley system needs to be adjustable. In this case the position of the pulley, the height along the tube, will be adaptable.
3. **To take into account**
   - Length of the triangle shape bars so they don't get in a blocking position when the guide is at the upper point and they don't hit the cable when the guide is at the lowest point.
   - The three bars connecting the mass and the guide. Make and end stop at the second bearing so that the bar closer to the guide can be shorter (turning point closer to the main vertical bar).
   - Calculation of forces and stiffness required for the spring: look at the length of existing springs with that stifness. Do they fit inside the tube? Is there enough space for adjusting the distance to the pulley?

5.4.2 Concept 2

1. **Functionality**
   The configuration is made of four bars connected to each other by means of bearings. The last link also allows 300mm of total up-down motion of the end-effector, the arm.
2. **Spring-pulley system**
   The spring pulley configuration can be located either in the first or second linkage. Three different spring configurations are possible, shown at the next section in the figures 16, 17 and 18.
3. **To take into account**
   - Calculation of distances for the adjusting of the mass compensation.
   - Maintaining the ROM with an easier assembly.

6 Conceptual Designs

In this section the previously introduced concepts are going to be analyzed in more detail. For that, the main focus is the mechanism of the bar containing the spring-pulley configuration. The worst case scenario is used to obtain the stiffness of the spring and from there on, a standard spring which would fit in the system is chosen.

A gravity equilibrator is a statically balanced system, which means that it has a constant potential energy, [9]. When forces are known, this following equation is applied:

$$U_p = U_m + U_s = m \cdot g \cdot l \cdot \cos\phi + \frac{1}{2}k \cdot (a^2 + r^2 - 2 \cdot a \cdot r \cdot \cos\phi) \tag{1}$$

With U_p as potential energy of the system, U_m as potential energy of the mass and U_s as energy stored on the spring.

$$\frac{\partial U_p}{\partial \phi} = -m \cdot g \cdot L \sin\phi + a \cdot k \cdot r \sin\phi = 0 \tag{2}$$

Gravity arm equilibrators depend on the configuration of the spring, and most of them use the concept of the zero-free-length spring. The spring force is proportional to the total length rather than to its elongation.[10]

In order to obtain that behavior in real life, a spring pulley mechanism is used. By using the concept of the zero-free-length spring, constant potential energy and zero moment at the pivoting point. From the first one can be derived the following equation[10]:

$$M \cdot g \cdot L = a \cdot r \cdot k \tag{3}$$

M: mass of the arm
L: length of the beam
g: gravity constant
a: distance from the pivoting point of the beam to the fixed spring attachment point on the vertical
k: stiffness of the spring
r: distance from the pivoting point to the spring attachment point on the beam.

The arm gravity compensator is in equilibrium for any position if equation 3 is fulfilled. Hence, looking at this equation, to adjust the compensation for different masses, either distance a or r should be modified to keep that equilibrium. For this design, distance a is going to be fixed and r will work within a distance range.

First, the distribution of the forces analysis is done, to have an overall idea of the force that the spring system is holding. It has been seen that the tensional force at the spring is very similar as if applying the external mass to the spring pulley configuration bar directly. Therefore, for simplification, that has been applied in this report.

To obtain the stiffness needed for the given distances, the worst case scenario is analyzed, which means to take into account an external arm mass of 4kg. This process is done by using different values for a and r, which are the design variables. With this, some spring stiffnesses are obtained and it is possible to see in the market if there are any standard springs applicable. For that, Tevema and Lesjofords catalogs have been checked.

Next is to check if any of these springs would fit any of the tow concepts described in this section. That is done by analyzing their natural length and extension and identifying the space they would need at each design and finally deciding if it is feasible.

6.1 Concept 1

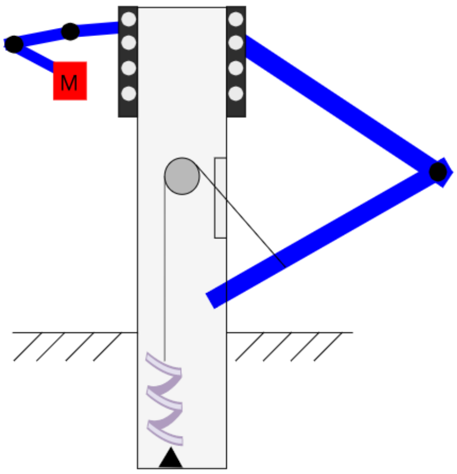


Figure 11: Concept 1

A. Force analysis

Some design parameters have been taken into account to obtain an estimation of the forces at the bar connected to the spring pulley system: the length of the bars and the mass of the bars.

With that, the reaction forces at each connection can be obtained and use them later to choose the bearings and the rolling guide. The following drawing (figure 12) shows the distribution of the forces of the beam connected to the spring system. Ts is the tension of the spring, m5 the mass of the beam and Rx4, Ry4, Rx5 and Ry5 the reaction forces.

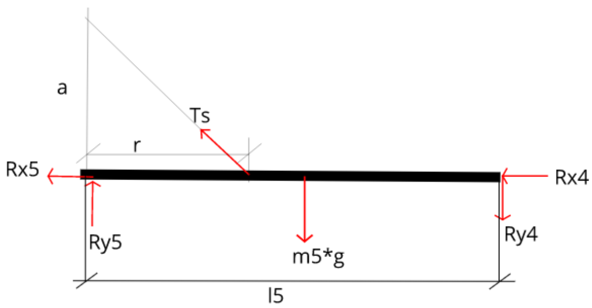


Figure 12: Force distribution of the bar connected to the spring-cable-pulley system

Applying the equation **??** to this case, the reaction force Ry5 represents the product of $M \cdot g$. Different spring stiffnesses and distance range r are tried to see which one could fit in the configuration. As an initial step, it has been chosen a distance a of 60mm, and from there on, by means of trial and error using a matlab script, a spring stiffness and distance range r have been chosen.

For the decision of the spring stiffness and distance r, the configuration requiring less force is taken into account.

B. Length of the triangle bars

A condition for the length of the bars connected to the guide line and the spring system is that they should be long enough to make the 300mm vertical ROM and that they should not get in a blocking position.

For that, trying different lengths L1 for both of the bars, and applying a height of 300mm that they have to achieve, the final angles are obtained. See figure 13 for a visual description. As a result, these angles should be higher than 15 degrees so the position is not locked. It has to be noted that this angle decision is based on experimenting with scaled pieces.

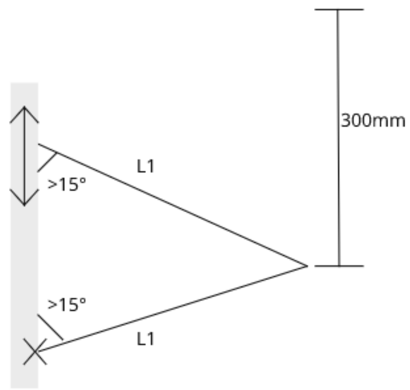


Figure 13: The two bars connecting the guide and the spring pulley system

6.2 Concept 2

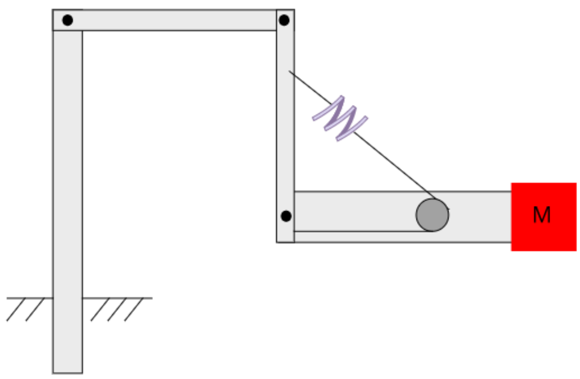


Figure 14: Concept 2

A. Force analysis

Figure 15 shows the force analysis at the second concept, similarly done as from the first concept. In this case, only the first bar, the one connected to the external mass and to the spring system, needs to be taken into account.

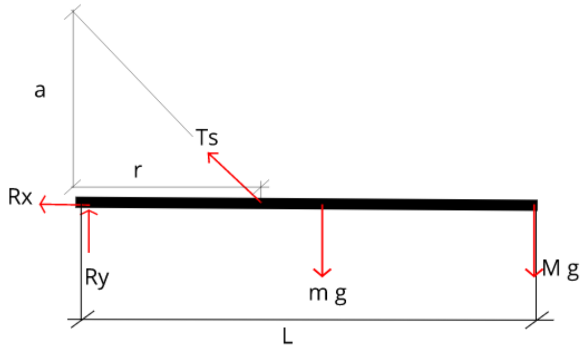


Figure 15: Force distribution of the bar connected to the spring-cable-pulley system

In order to obtain the unknown forces, a moment equilibrium around the pivoting point (where Rx and Ry are applied) is done. The bars' length and masses are initially estimated using the actual MASMini data as a guidance.

From a given height a, the stiffness k and the range of distance r are obtained by applying equation **??**.

B. Spring configuration

For this concept three different spring configurations, shown in figures 16, 17 and 18, have been analyzed. The force analysis is the same for each configuration. However, the distances and the location of the spring at the beam are different. Thus, not only the stiffness of the spring is taken into account in this analysis but also the extension of the spring is considered.

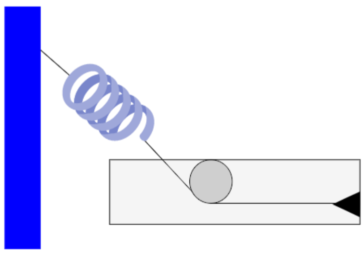


Figure 16: Configuration 1 of the spring pulley system

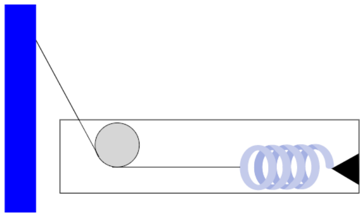


Figure 17: Configuration 2 of the spring pulley system

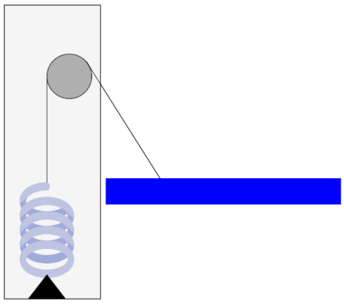


Figure 18: Configuration 3 of the spring pulley system

6.3 Decision

Subsequent step is to check if there is a standard spring with the given stiffness in the market and if the extension length it takes can fit in the designed space. This will show whether concept 1 or any of the concept 2 spring configurations are feasible or not.

The following table 2 contains the two springs considered for concept 1 and concept 2 configurations respectively.

Spring name	Company	Natural length	Extended length	Force	Stiffness
3525	Lesjofords	70 mm	130 mm	194 N	2.7 N/mm
7624	Lesjofords	120 mm	160 mm	138.7 N	2.74 N/mm

Table 2: Springs data

It has be kept in mind that the lower the force used to adjust the mass compensation the better, therefore, the configuration requiring less force will be chosen.

The simplicity of assembly needs to be considered as well. Thus, concept 1 would not be a good choice since the placement of the spring inside the tube and the configuration of the linear guide would take a lot of time and would not be a simple process.

All in all, concept 2 is chosen and a further analysis is done to study what the 3 possible spring configurations. A more detailed design of the adjusting of the mass compensation system will also be described and analyzed.

7 Detailed Design

In this section the chosen concept will be developed in more detail. First, the three spring configurations are analyzed and one is chosen. The forces, the designed and redesigned parts and the selection of joints for the assembly will be determined. A testing of the designed mechanism is shown and, finally, an estimation of the cost of the mechanism is reflected in a BOM.

The images and values of the force simulation of the redesigned pieces are shown at the Appendix B 11.3 Force simulation with SolidWorks.

7.1 Spring configuration selection

For configuration 1 (figure 16), when the end effector reaches 150mm upwards, the distance is smaller than any spring length, therefore this configuration is excluded.
For configuration 3 (figure 18), the extension of the spring does not fit the length of the beam, taking into account that designing a beam longer than 376mm is not fitting the home use safety and ergonomics requirements. Distance 376mm is taken from the actual length of one of the bars of the MASMini.
All in all, configuration 2 (figure 17) is chosen, the one the actual MASMini is using.

Seeing this, it is concluded that for simplicity, the MASMini beam, pulley and spring are going to be used, subjected to modifications if needed. With this decision, the stiffness of the spring is given and therefore the distance 'a' has to be chosen and from there obtain the rest of parameters.

7.2 Range of distance 'r' selection

Since the MASMini is taken as a guidance, the main mechanism will be the focus point on the following detail analysis. It involves the connection of the piece with the origin of the cable, and the beam containing the spring pulley system.

Given the distance a = 20mm, and applying the lightest mass, 1kg, the minimum distance r to be in equilibrium would be 20.2mm.

$$r = \frac{MgL}{ak} \tag{4}$$

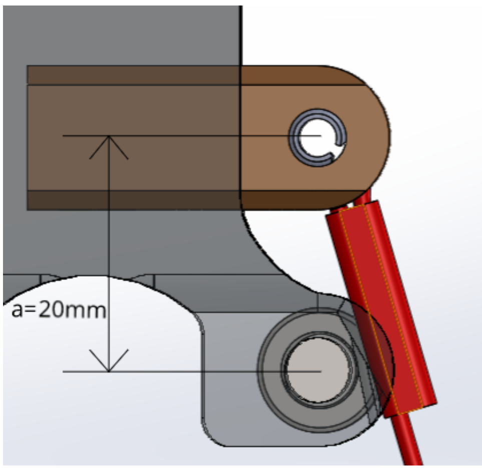


Figure 19: Connection piece containing the origin of the cable. Distance a is shown.

With this value as a starting point, the connection of the cable to the pulley is analyzed. It can be seen that a minimum distance is required for placing the pulley so there is no collision. It can be seen in figure 20, and that distance is r = 21.5mm. Therefore, from this value of r, the minimum mass compensation is calculated: 1.065kg. Based on this, the new calculations are shown in the table 3.

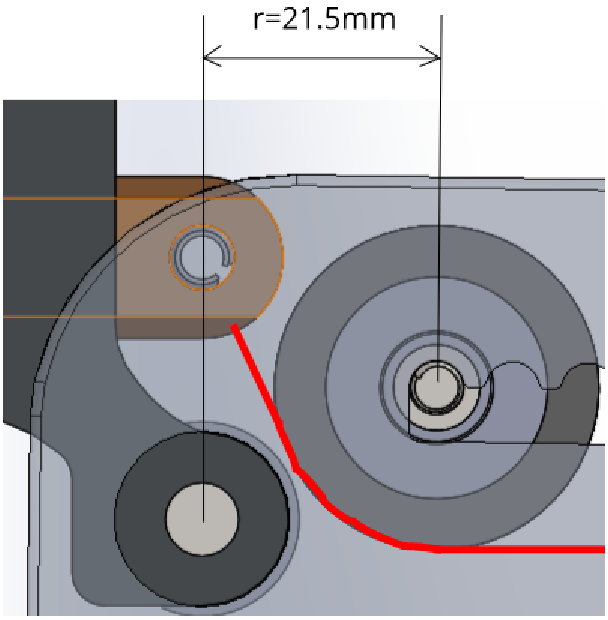


Figure 20: Connection of the cable (red) with the pulley of the beam

a[mm]	r[mm]	M[kg]	g[m/s^2]	L[mm]	k[N/mm] [1]
20	21.5	1.065	9.81	300	7.28
20	84.5	4.18	9.81	300	7.28

Table 3: Distance range for min. and max. mass compensation

Once the range of distances are obtained, the forces needed to adjust the mass need to be calculated. For that, the force distribution diagram shown in figure 21 is used and the following equation is derived.

$$\sum M = 0 \tag{5}$$

$$0 = -M \cdot g \cdot L \cdot \sin(\alpha) + T_{s,x} \cdot r \cdot \cos(\alpha) + T_{s,y} \cdot r \sin(\alpha) \tag{6}$$

$$T = \frac{M \cdot g \cdot L \cdot \sin(\alpha)}{r \cdot (\sin(\gamma)\cos(\alpha) + \cos(\gamma)\sin(\alpha))} \tag{7}$$

$$T_{s,x} = T \cdot \sin(\gamma) \tag{8}$$

$$T_{s,y} = T \cdot \cos(\gamma) \tag{9}$$

r : distance from the turning point to the center of the pulley in the bar.
T : tension force on the cable.
M : mass of the arm
L : length of the bar.
α : minimum angle of the beam with the vertical.
γ : angle of the cable with the vertical at the α angle situation.

[1] Data from Tevema

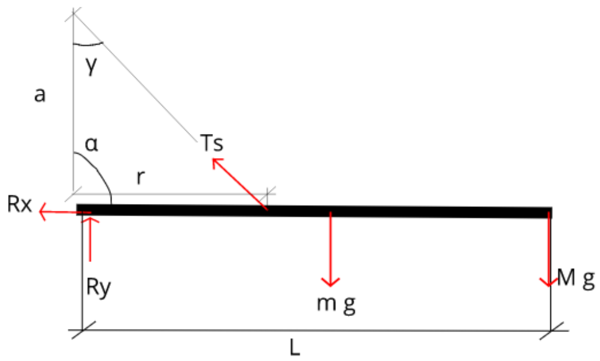


Figure 21: Force distribution of the bar connected to the spring-cable-pulley system

Applying it to the worst case scenario and to the closer distance mass adjustment, the forces affecting the pulley are the following, shown in table 4.

M[kg]	T_s[N]	$T_{s,x}$[N]	$T_{s,y}$[N]
4.18	85.54	20.33	83.09
1.065	26.03	6.19	25.29

Table 4: Tension forces at the pulley

Placing the mechanism in SolidWorks without any interference, the following angles α and γ are obtained, shown in table 5.

M[kg]	γ[°]	α[°]
1.065	13.75	18.02
4.18	13.95	28.04

Table 5: Angles for two mass compensation scenarios

7.3 Mass compensation adjustment mechanism

Once the distances are obtained, the mechanism to adjust the mass compensation needs to be designed. Two options have been considered, first by means of a button and some wholes defining the different compensation levels, and on the other hand by means of some teeth shape at the sides of the beam.

7.3.1 Button adjustment

The first option for the design of the main beam is to adjust the mass compensation by means of a push button in small holes on the upper part of the beam as it is shown in figure 22.

This system allows small holes, which means more choices for the adjustment. However, the smaller the hole the more difficult it is for someone to press it.

The push button is designed so it is connected to the pulley through the same axis (see figure 23). Its shape and thickness allows it to work as a spring. To move it from hole to hole it is necessary to help it by moving the shaft backwards/forwards from both sides of the beam. Hence, for the mass compensation both hands will be used.

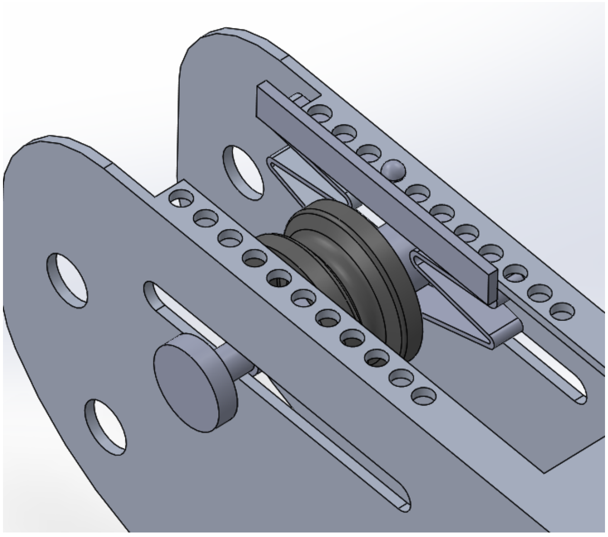


Figure 22: Button adjustment beam design

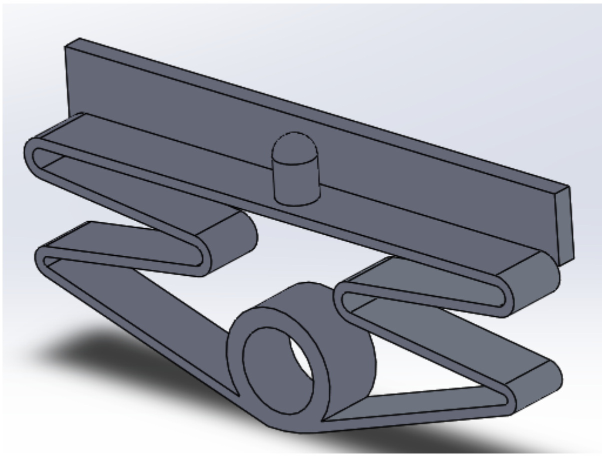


Figure 23: Push button for the adjustment

7.3.2 Teeth adjustment

The second option for the mass adjustment mechanism design is based on a teeth shape design, see the figure 24. With that shape on the sides of the beam, the pulley needs to be pushed downwards and at the same time forwards or backwards to move it from one level of mass compensation to another. For that, a 'hand-holder' called assembly is used which allows the user move the pulley and the shaft easily. See figure 25.

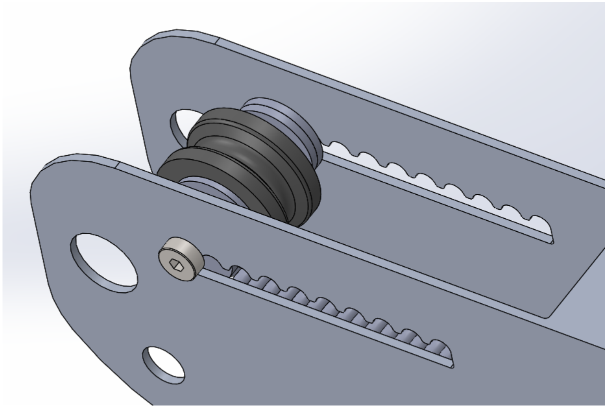


Figure 24: Teeth adjustment designed beam

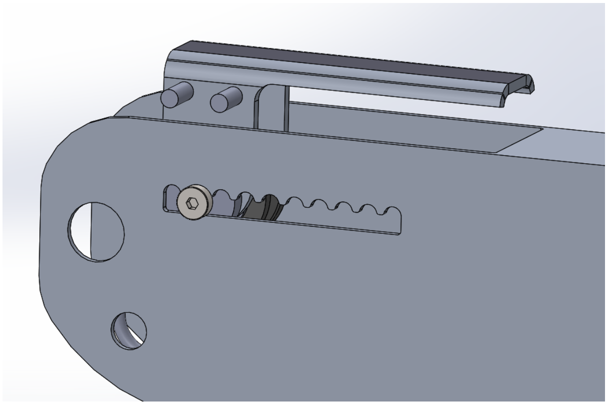


Figure 25: Teeth adjustment with the hand holder

7.3.3 Decision

Having analyzed the first design, the button piece and part of the beam have been 3D printed to see how that mechanism would work. It has been seen that the holes are too small to push them, and making the button bigger and therefore, the holes, results in less adjustment levels. The second design, the teeth shape adjustment mechanism design is then further developed. For that, special attention needs to be taken to the hand holder piece since it falling can cause collision with the cable.

7.4 Hand holder assembly

Going into more detail about the teeth shape adjusting mechanism, the assembly containing the pulley and shaft is described here. This subassembly combines the shaft, pulley, hand holder piece, shoulder bolts and rest of the fasteners such as bearings and retention rings as it can be observed in figure 27 and 28. First, the distances and the mass compensated at each distance is calculated. Shown distances refer to the placement of the center of each teeth shape circle, and the results are shown in the table 6 below.

M[kg]	1.06	1.41	1.76	2.10	2.45	2.80	3.14	3.49	3.83	4.18
r[mm]	21.5	28.5	35.5	42.5	49.5	56.5	63.5	70.5	77.5	84.5

Table 6: Mass compensation adjustment distances at the beam

The main part, the hand holder, is a folded metal piece of 3 mm thickness that withstands

the user's forces when pushing. The detail design of it can be seen in the drawing 35 at the appendix B (section 11). The minimum required force to move the pulley has been calculated, however, a person can exert higher forces than that. Therefore, for its design higher forces need to be taken into consideration.
The two pins at one side have the purpose of stopping the piece to rotate and collide with the cable.

To calculate the minimum necessary force to move the pulley, the perpendicular force to the cable is taken into account. For that, the scenario where the mass compensation is minimum is taken into account. At that situation, the beam is not lowered down at its maximum position, thus the angle of the beam with the vertical will be higher and the force as well. Using the model of the assembly in SolidWorks, the angle between the cable and the perpendicular is obtained. See figure 26 for the schematic forces. The perpendicular force is obtained by using the following equation 10 concluded from the force scheme.

$$F_p = T_s \cdot \cos(angle) = 26.03 \cdot \cos(86.15) = 6.32N \tag{10}$$

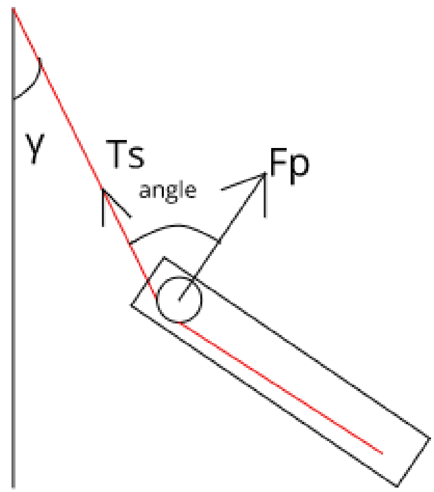


Figure 26: Calculation of the perpendicular force F_p to the hand holder

At table 7 the tension force of the cable and the necessary force for the hand holder to move at two scenarios is shown.

Mass compensation scenario [kg]	Ts [N]	Force (Ts) perpendicular to the bar[N]
1.065	26	6.32
4.18	85	5.75

Table 7: Applied force to the hand holder for the mass compensation adjustment

Going to the rest of the parts of the assembly, first the shaft is described. Its drawing can be seen in the figure 34 at the Appendix B, section 11. To make the assembly easier and have it in one piece, only one side ends with a bigger diameter. The outside diameter is 8mm and the inner diameter is 5mm.

Therefore, the chosen shoulder bolts have M5 metric, placed at each side of the hollow shaft. They are not completely introduced in the shaft, and the stepped out part will be in contact with the beam and will allow to fix the pulley at the different stages of the mass compensation distance. In the figure 27 it can be appreciated how one part stays outside the shaft sides to have a space to be in contact with the beam holes.

In order to connect everything and prevent the twisting of the hand holder, some retention rings have been placed between the bearings and the hand holder and one side of hand holder. It can be seen in the section view at figure 28.

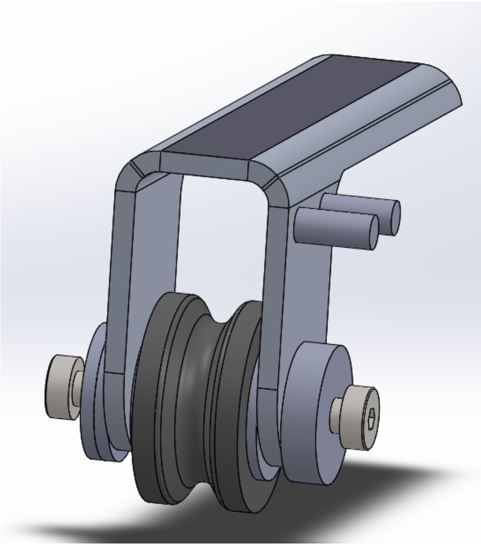


Figure 27: Hand holder subassembly

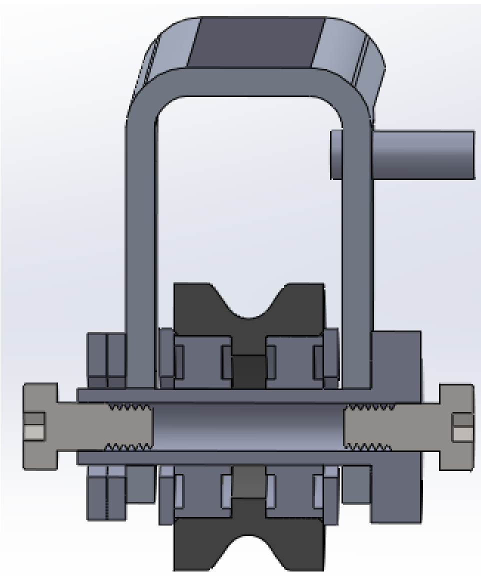


Figure 28: Section view of the hand holder subassembly

7.5 Redesigned pieces

7.5.1 MM-1.001-AE

This piece is called ”spindelhouder” (see drawing MM-1.001-AE, figure 31, in appendix B) and it has been modified from the original one from the MASMini. This approach has been taken instead of a complete new designed piece because the initial purpose was to have a prototype where actual pieces could be modified. Thus, the principal modification has been taking some material out so it allows the cable to have a smaller angle γ. With a smaller cable-to-vertical

angle lower forces are obtained.
Second main change is the modification of the of M8 hole instead of M10 at the connection with the beam.

Figure 29: Spindelhouder piece

7.5.2 MM-1.003-AE Bar

This part is the beam carrying the pulley cable spring system. The redesign of this piece can be seen in detail in the drawing 33 at the appendix B, section 11.
As it has been previously mentioned, the teeth design is used for the adjustment of the mass compensation and the diameter of the holes is 5mm.

7.6 Selection of joints

1. Union bar-spindelhouder

   - Bearings:
     The reaction forces at the connection point are calculated doing the equilibrium of forces at the beam giving as a result:

$$R_y = 43.96N \tag{11}$$
$$R_x = 20.36N \tag{12}$$
$$R = \sqrt{R_x^2 + R_y^2} = 48.45N \tag{13}$$

     Seeing these results, the bearings that were being used at the MASMini can be used: F 6800 ZZ, from Neita. They withstand a dynamic load of 175 N and a static load of 85N.

   - Screws:
     The connection hole is now M8 shape, therefore new screw bolts need to be used. For that, Misumi HDMSB8-20-F6-M8 screw bolts have been chosen.

2. Union pulley-bar

   - Bearings:
     The bearings currently implemented in the pulley have the dynamic and static loads

of 225N and 88N respectively. The reaction forces at the pulley, taking into account the pushing of the hand holder and the cable tension are below those values, therefore the same bearings are used: 698 ZZ from Neita.

- Screws:
  Misumi HDMSB5-10-F5-M5 have been chosen for both sides of the pulley connection.

7.7 BOM

Assembly	Part	Description	Company	Price	Surface treatment	Quantity	Total price
	300.16	t connection 25mm	ernst&brinck	6.5	7.5	1	14
	MM-3.002	tube 25x19x340	staalmarkt	4.18	5.25	1	9.43
	MM-3.005-AE	tube clamp 25 mm	peters	11.87	5.5	1	17.37
	MM-1.003-AE	Setting unit, 1 vertical bar	peters	14		1	14
	100.15	6802ZZ	neita	0.65		2	1.3
	MM-1.001-AE	Spindelhouder	peters	7	7.5	1	14.5
	100.12	pin cable	fabory	0.22		1	0.22
	MM-1.006	Cable guide	hankamp	19.8		1	19.8
	MM-1.004	Cable	lijnenspecialist	2		1	2
	200.15	ball head nut m8	fabory	0.1		2	0.2
	MM-X.109	Wire rod M8x40	fabory	0.1		1	0.1
	Shoulder Bolt M8	HDMSB8-20-F6-M8	misumi*	7.65		2	15.3
	MM-X.113	913.3-M825-KU	drabbe	0.9		1	0.9
	700.7	Knurled knob	fabory	0.88		1	0.88
	MM-X.604	Wire bus	fabory	0.6		1	0.6
	MM-2.004	end piece lower beam	peters	18	7.5	1	25.5
	200.17	bolt m6	fabory	0.1		2	0.2
	MM-X.107	M10x16 bolt	fabory	0.1		2	0.2
	MM-X.403	F 6800 ZZ bearing	neita	1.4		3	4.2
	200.8	ring (d10.04D15.95B1)	fabory	0.06		2	0.12
	MM-X.206	low nut M10	fabory	0.15		2	0.3
	200.26	low head nut M10	fabory	0.12		1	0.12
	MM-X.108	M8x10 bolt head	fabory	0.1		2	0.2
	400.7	rubber piece	technirub	0.05		4	0.2
MM-2.000-AE	MM-2.001-AE	lower beam	baas	10.2	5.5	1	15.7
	RetRing3	WasherB2D19.5d10.5	fabory	0.03		2	0.06
	RetRing2	WasherB1.5D20.5d10.5	fabory	0.03		2	0.06
	MM-X.402	698ZZ bearing	neita	0.6		2	1.2
	MM-2.016	spring T32950	tevema	4.26		1	4.26
	HH-Sheetmetal-AE	hand holder sheet metal	***	4.54		1	4.54
	Small pin hh -AE	plastic pin		0.01		2	0.02
	MM-2.015-AE	Modified shaft	peters	3		1	3
	MM-2.003	pulley Dmax30	graaf	3.55		1	3.55
	Shoulder Bolt M5	HDMSB5-10-F5-M5	misumi*	8.69		2	17.38
	F688ZZ bearing	Miniature ball bearing flange 2-sided steel seal (dust-proof)	neita**	4.39		2	8.78
MM-2.200	mm-2.010	pulley housing	peters	13		1	13
	200.1	10x60pin joint	fabory	0.2		1	0.2
	200.24	ring 8mm		0.05		3	0.15
	MM-2.003	pulley Dmax30	graaf	3.55		1	3.55
	MM-2.015	Shaft	peters	3		1	3
	MM-X.402	698ZZ bearing	neita	0.6		2	1.2
	MM-X.304	circular clip 8mm	fabory	0.1		1	0.1
				Total		**64**	**221.39**

*Price for more than 20 units

**Price for 1 unit

***Price for 50 pieces

Figure 30: BOM list of the redesigned model's mechanism

8 Conclusion

It can be concluded that a redesign of the mechanism of an arm gravity support has been developed during this internship. First, some existing different gravity arm supports have been looked at to see the differences between mechanisms and their characteristics compared with the actual MASMini from Saebo, and the requirements for the new design have been defined. From a morphological map six pre-concepts have been obtained and with the use of weighting factors, two concepts have been selected and further described. From there on, one has been chosen and described in detail, which has become the final mechanism design. Finally, some force simulations have been made by means of SolidWorks and the designed pieces have been 3D printed and tested.

Looking at the goal and tasks described at the beginning of the report, it can be said that existing mechanisms have been analyzed and from there on, the developed mechanism has had always the aim of needing the minimum forces from the user.
A BOM list has been made showing the expected prices of the assembly parts of the main mechanism. It can be said that the number of parts has decreased and the final price is around 30€ cheaper. It has not reached the 100€ of difference for the mechanism, which is deduced from the requirement of making the overall product 200 cheaper. However, looking at the parts and standard fasteners proposed, it is possible to optimize the resultant price. For example, by customizing a specific fastener, or doing a complete new design of pieces that in this internship only have been modified. These comments will be made at the next section, 9, Recommendations.

As a final conclusion, the redesign of this mechanism leads to the next step which would be to analyze how to connect this mechanism to the overall product, deriving to the final gravity arm compensation support so patients can buy it and use it at home.

9 Recommendations

In this section some aspects for future research are given as well as improvement comments on the designed pieces.

1. **The design of the teeth of the beam.** The given diameter is 5mm while the shaft has the same dimensions. In order to let the shaft move without any problem the teeth can be designed with a diameter of 5.1 or 5.2 mm. Secondly, the beam is machined with laser cutting. The precision of this operation is ± 0.1, therefore, it has to be analyzed how important the precision is for this part of the design. It will not be a critical factor, however, when doing the simulation of forces, the resultant force will be applied on a point instead of a surface. Thus, results will differ and it needs to be analyzed if the same geometry or material will withstand the stresses.

2. **Levels of the mass compensation.** The minimum mass compensation is for 1.065kg. Concerning the safety of the user, a 0kg of minimum mass compensation would be the ideal design so when the arm is no longer held by the device, this would not suddenly lift up. However, in this mechanism distances were too close and the design of the 'spindelhouder' did not allow a closer start for the teeth shape holes since the pulley would collide with that piece. When redesigning the 'spindelhouder' again, this aspect needs to be taken into account to be able to allow a minimum compensation of 0kg.

3. **Joints for the complete assembly.** Next step is to connect the mechanism to the rest of the links to make the overall product. For that, further research needs to be done in terms of joint connections.

4. **Elbow support connection.** An important fact of the final product is the elbow support. The designed mechanism will act as second link, which means that will have the elbow support directly connected to it. An extra piece/connection needs to be designed because if the actual connection from the MASMini is used, it will either be above or below the beam. This means that the user will have to make extra force to move the arm if it is placed below; and if it is fixed above, the patient will not be able to go completely down with the arm because the mechanism beam is blocking that.

10 Appendix A

In this first appendix I will talk about my experience at the company, what I have learned and least but no less important, about the office atmosphere.

With this internship I can say that I have learned how an arm gravity compensator works, and the principles behind it. At the time of redesigning some parts, I also figured that the assembly is as important as the simulation of the forces to see if the design will work.

I have also been able to be in a tour of the grinding machines of the factory, below the rehab office, but the most visited machine has been the coffee machine.

At the rehabilitation department there are six people working at the moment: Jos (marketing), Laura (industrial designer), Claudia (research manager and engineer), Koen (engineer production manager), Yvon (product adviser and product specialist), and Freek (CEO). The working atmosphere is both professional and friendly, which helps to be confident to ask each other for advise and maintains the day entertaining.

Language can be sometimes a barrier, but instead of seeing differences as an impediment, you have to take advantage of them and learn. And that is what we tried to do by having each day (or the days we remembered) a word translated in Spanish and Dutch, so both sides could learn a little bit.

What I can say is that overall I finish with a positive feeling and that I have learned things that I will use in future projects.

11 Appendix B

11.1 Morphological map

Function	Concepts				
Mass compensation	Counterweight	Auxiliary linkages	-	-	-
Auxiliary linkages	Parallelogram	Triangular	Sarrus	Peaucellier	Chebyshev
Provide additional motion	Guide	Wheels- Guide roller	Bar (1 or 2 DOF link)	-	-
Tension	Ideal spring	Pulley- string-spring	Gas spring	Rubber bands	Torsion spring
Tension adjustmentt	Spindle	Clip	Fixed holes	Lever	-
Ergonomics	button and go directly to level 0 (no tension)	-	-	-	-
Safety blocking system	Clamp	-	-	-	-
Forearm support	Steel support with velcro	Foam support for the elbow	Elastic material	-	-
	Moving backwards/forwards	Small rotation for adjustments	velcro for the thumb (poka-yoke)	-	-
Height adjustment	Bar lever pressure	Scissor lifts	Bar screw	-	-
Table mounts (table/wheelchair)	Press mount	Clip fixation	Standard fixation	-	-

Table 8: Morphological map

11.2 Technical drawings of the redesigned parts

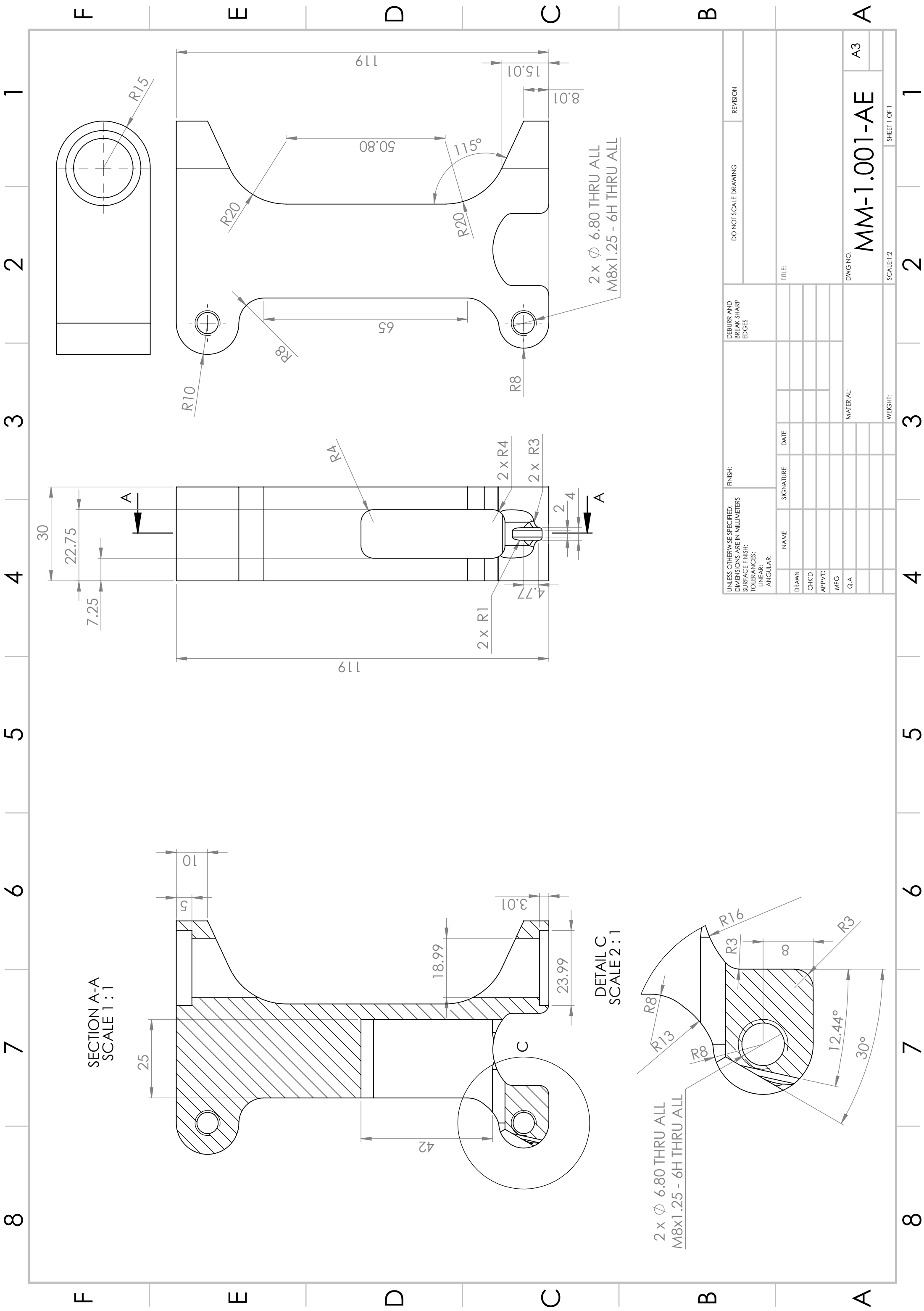
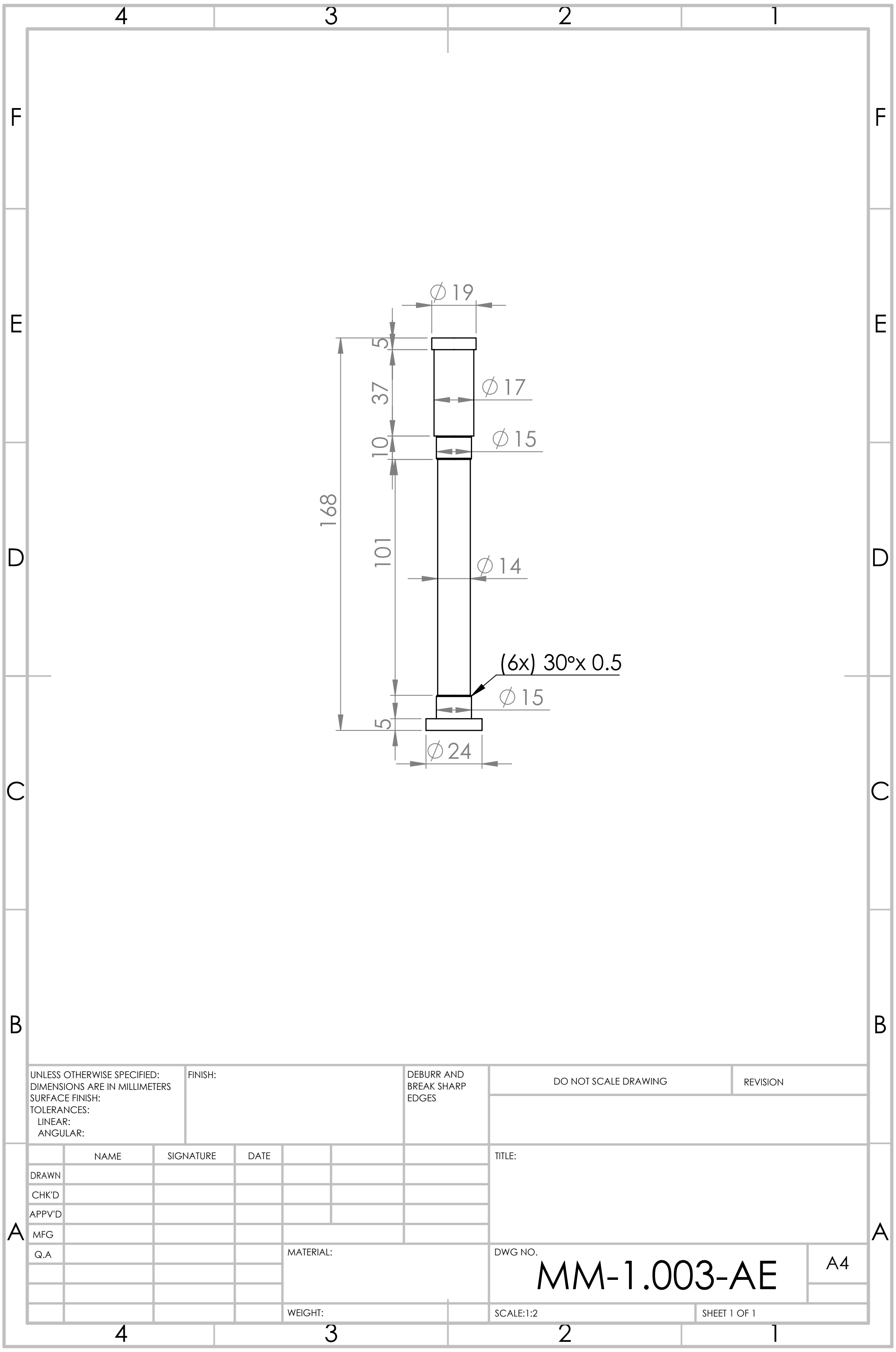


Figure 31: MM-1.001-AE, "spindelhouder"



∅19
5
37
∅17
10
∅15
168
101
∅14
(6x) 30°x 0.5
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UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
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DEBURR AND BREAK SHARP EDGES
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REVISION
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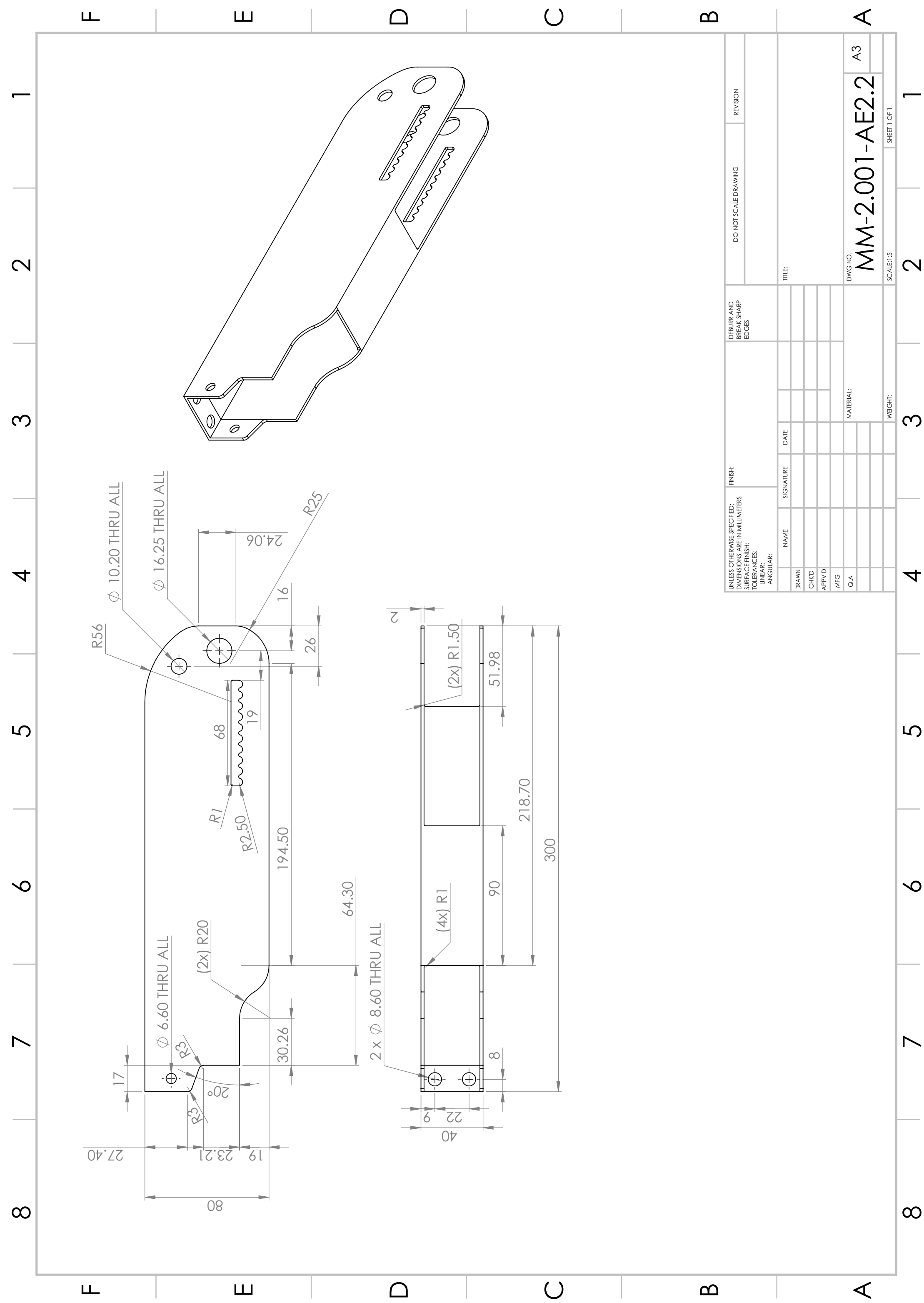
Figure 32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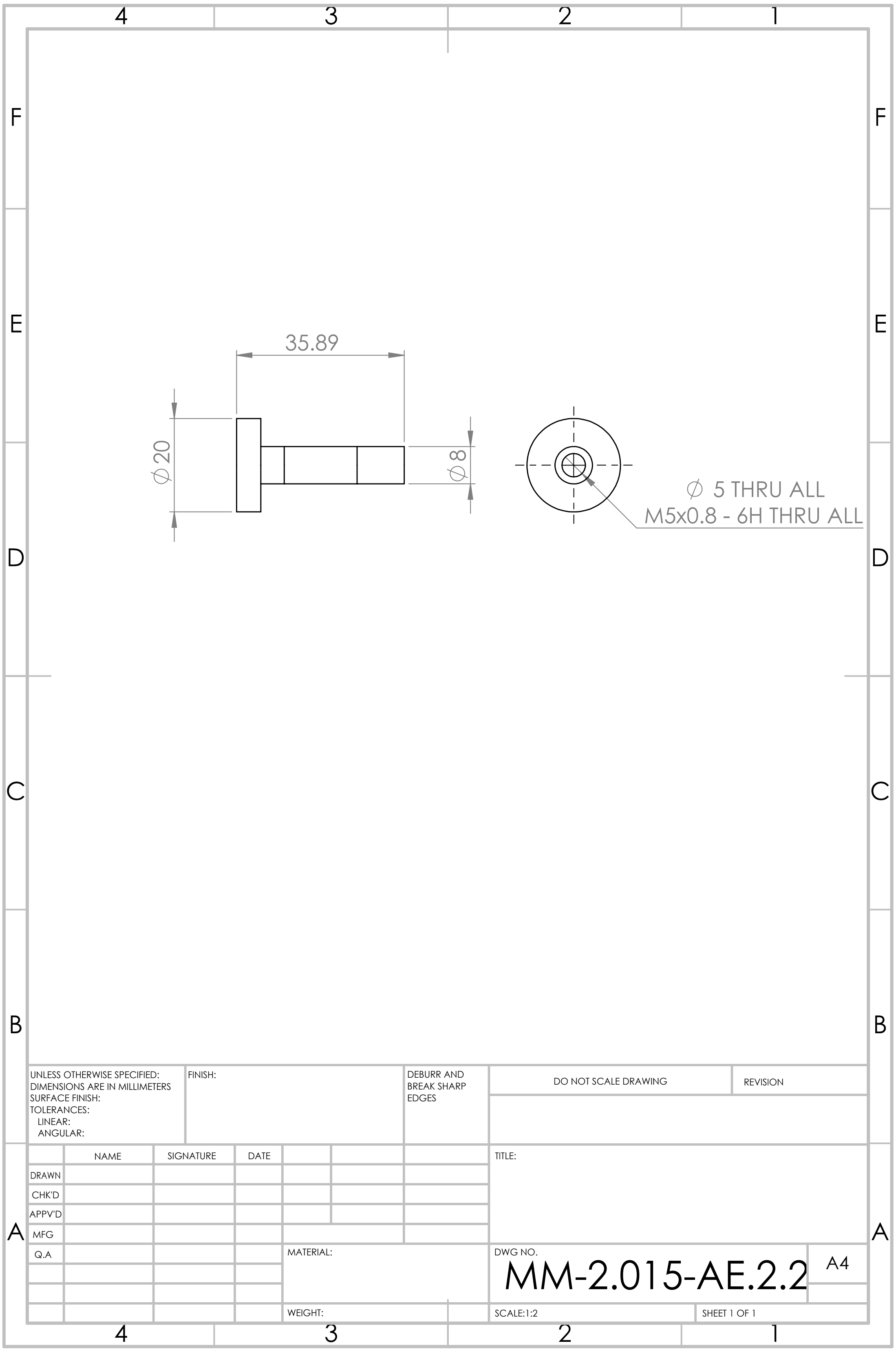
Q.A
Ø 10.20 THRU ALL
Ø 16.25 THRU ALL
Ø 6.60 THRU ALL
2 x Ø 8.60 THRU ALL
R56
R25
R1
R2.50
(2x) R20
R3
(2x) R1.50
(4x) R1
24.06
16
26
19
68
194.50
64.30
30.26
17
20°
27.40
23.21
80
2
51.98
218.70
300
90
8
6
22
40

Figure 33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SHEET 1 OF 1

Figure 34

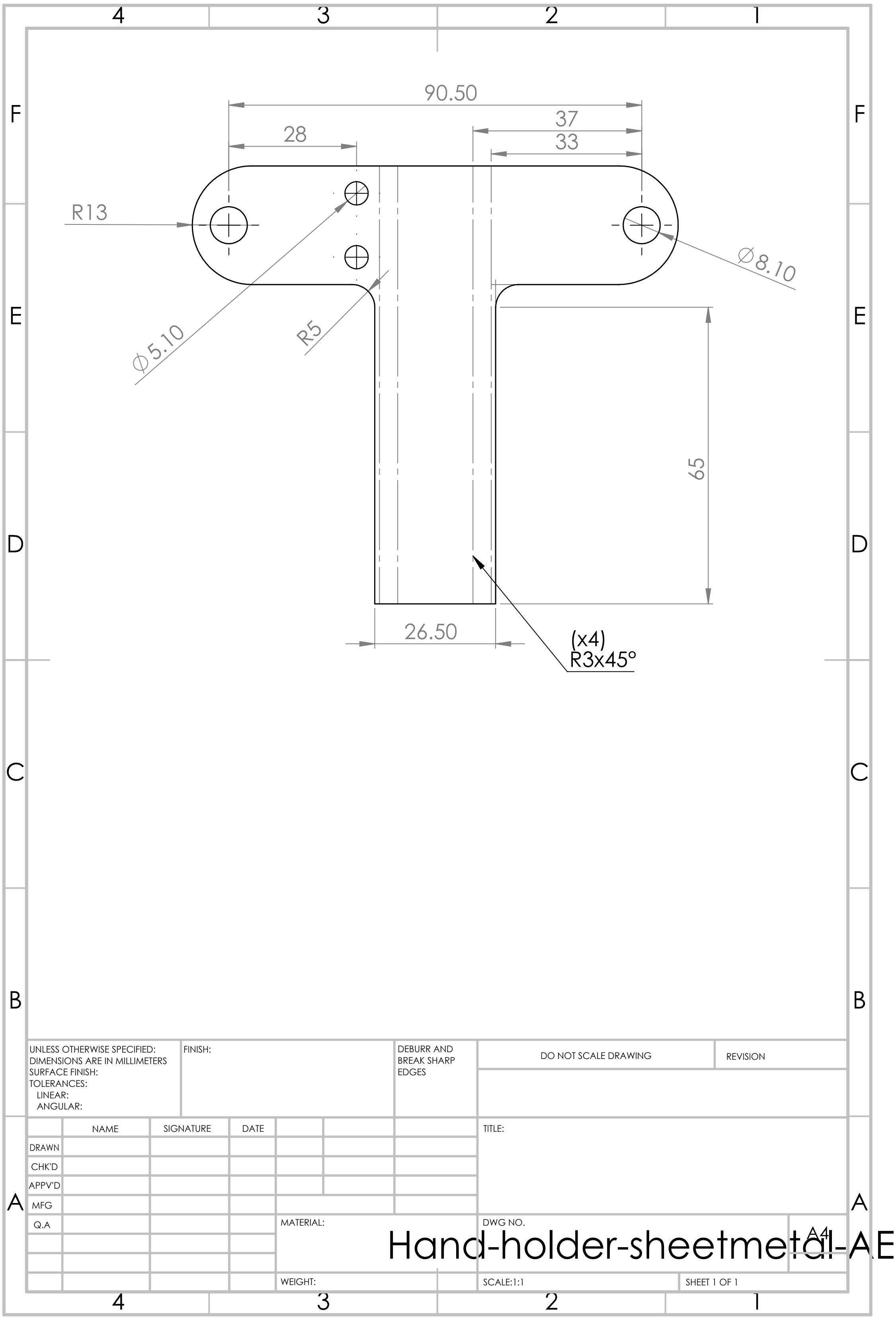
90.50
37
33
28
R13
Ø8.10
Ø5.10
R5
65
26.50
(x4)
R3x45°
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
TITLE:
DRAWN
CHK'D
APPV'D
MFG
Q.A
MATERIAL:
DWG NO.
Hand-holder-sheetmetal-AE
A4
WEIGHT:
SCALE:1:1
SHEET 1 OF 1

Figure 35

11.3 Force simulation with SolidWorks

At this section the simulation of the forces done for each part is showed, and in the table 9 their safety factor is showed relative to the applied force. It is obtained by doing:
safety factor = yield strength/max. stress. A valid safety factor for devices that are related to human applications is 4.
The applied force for the analysis at the shaft and hand holder are 200 N in order to show a scenario where the user exerts more forces than the minumum required to move them.

Part	**Material**	**Applied force [N]**	**Force direction**	**Safety factor**
Beam	Aluminum alloy	85	Normal to the surface	4.035
Shaft	Alloy steel	85, caused by the pulley	Normal,at the middle	3450.50
Shaft	Alloy steel	200, caused by the hand holder	Normal,at the sides	437.21
Hand holder	Alloy steel	200	Perpendicular to the beam	4.10

Table 9: Safety factor of the redesigned part respect to the applied force

The following figures show the stress results of the static simulations. The green arrows are normal to the fixed surfaces and the purple/orange arrows show the direction of the applied force for each case.

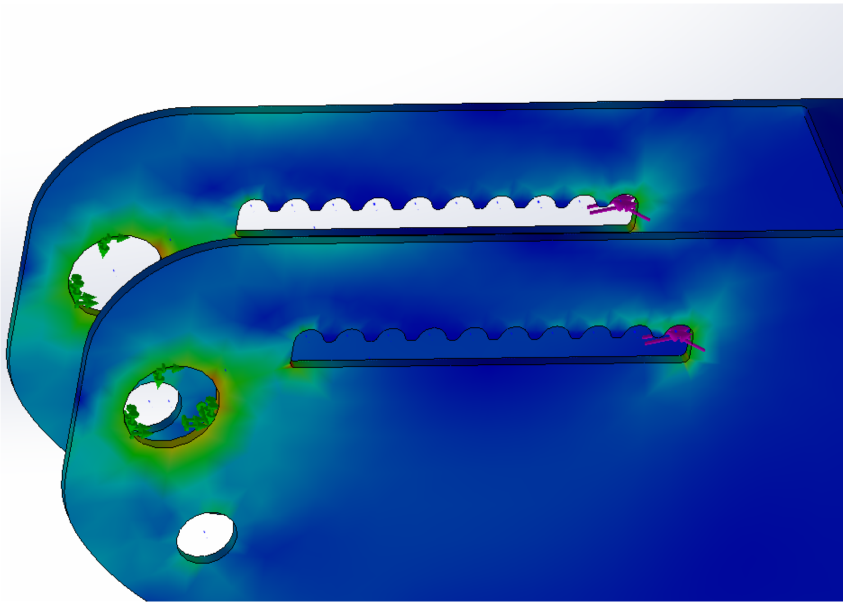

Figure 36: Stress distribution of the beam

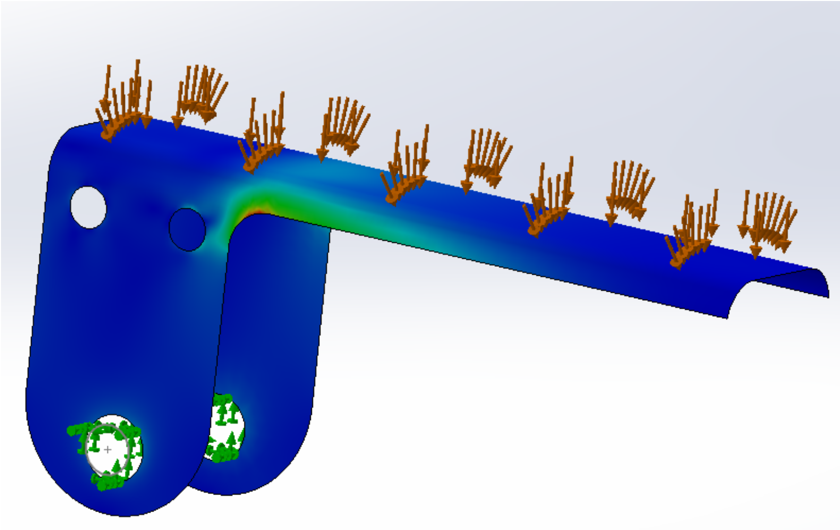

Figure 37: Stress distribution of the hand holder

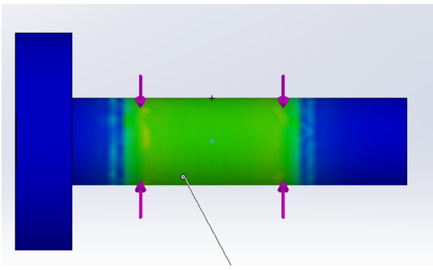

Figure 38: Frontal view of the stress distribution of the shaft

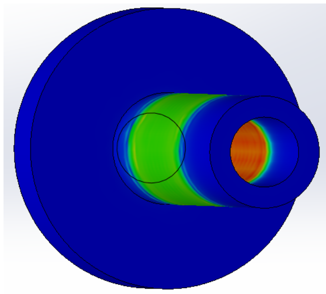

Figure 39: Inside view of the stress distribution of the shaft

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