Test Equipment for the LUCAS Chest Compression System

Incorporating Biomechanical Insights for Future Design Enhancements

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Abstract

The LUCAS Chest Compression System is a market leading mechanical cardiopulmonary resuscitation device, assisting medical professionals worldwide when treating patients with sudden cardiac arrest. The objective of this master thesis project was to develop a new, adjustable test equipment for the LUCAS device, allowing for tests on varying chest heights and stiffness levels. Product development strategies were utilized to develop the new test equipment, alongside with a biomechanical study, consisting of a literature search and a clinical data analysis. The biomechanical study unveiled realistic ranges and averages for chest height and stiffness that could be directly implemented in the test equipment. Possible future enhancements, for example using non-linear spring modules to more accurately mimic the chest's behaviour during compression were also identified. The final outcome includes a detailed CAD-model and a first physical prototype of a new test equipment for the LUCAS device, which is adjustable in chest height but not yet chest stiffness. The concept is based on an innovative tension-compression spring module that was developed to replicate the biomechanics of the chest during both compression and decompression. Serving as a proof of concept, this prototype is a first step towards a new, fully adjustable test equipment, made to validate the lifesaving LUCAS device.

Keywords: Mechanical CPR, Cardiopulmonary Resuscitation, LUCAS Chest Compression System, Test Equipment, Chest Biomechanics, Chest Stiffness

Abbreviations

AED Automated External Defibrillator

AHA American Heart Association

AIS Abbreviated Injury Scale

BMI Body Mass Index

CEM Concept Evaluation Matrix

CPR Cardiopulmonary Resuscitation

ERC European Resuscitation Council

IHCA In-Hospital Cardiac Arrest

ILCOR The International Liaison Committee on Resuscitation

LISA III The test equipment developed in this project

LUCAS Lund University Cardiopulmonary Assist System

OHCA Out-of-Hospital Cardiac Arrest

Preface

This master's thesis was conducted during the fall semester of 2023, and presented in January 2024. The project was carried out in collaboration with Jolife AB, a biomedical company based in Lund, a part of Stryker. The company designs, develops and manufactures the LUCAS Chest Compression System, a medical device that helps lifesaving teams around the world save sudden cardiac arrest patients.

First of all, we would like to start by thanking the entire team at Stryker/Jolife AB, for the welcoming atmosphere and generous assistance. Namely, we want to aim a special thanks to Jon Bylund, without whom we would not have gotten the opportunity to take on this project. We also want to thank Tobias Svahn for his invaluable guidance and advice. Finally, this project would not have been possible without Wiktor Kocula, our main supervisor, whose efforts have been essential to the success of the project. Thanks for going above and beyond for us and for being incredibly generous with your time and knowledge.

We also want to extend our gratitude towards our two LTH supervisors, Ingrid Svensson and Joze Tavcar, for their expertise within biomechanics and product development respectively. Thanks to Johan Nilsson and Ola Jakobsson at LTH for insights and ideas related to sensor selection. Finally, thank you Martin at Lesjöfors for guiding us in spring manufacturing and selection.

1 Introduction

A new version of the mechanical cardiopulmonary resuscitation (CPR) device, the LUCAS Chest Compression System, is under development by the R&D team at Stryker/Jolife AB, see Figure 1. The main purpose of the LUCAS device is to assist medical personnel in their efforts to revive cardiac arrest patients. To more accurately evaluate and validate this new version of LUCAS, a new test equipment is needed. There exists a current solution - a test equipment going by the name LISA, with the main purpose of ensuring the LUCAS device operates as intended to. However, this test equipment is out-of-date, not compliant with the new version of LUCAS and lacks several functionalities sought after by the development team. Namely, the current solution has a fixed set of springs connected to the compression plate, and thus a fixed chest stiffness. Furthermore, it can only test LUCAS at a limited chest height range. In reality, people have varying levels of chest stiffness and heights. There is thus a need to test the LUCAS device on a wider range and to better mimic real world scenarios. These improvements are crucial to validate that the LUCAS device functions optimally for all.

Figure 1: The LUCAS Chest Compression System with its transportation case.

1.1 Project Aims and Objectives

The main objective of this project is to develop a new test equipment, the LISA III, that can measure output from the LUCAS device in terms of compression force, depth, rate and recoil at different chest heights and for different levels of chest stiffness. Thus verifying that the LUCAS device adheres to the standards set for CPR and performs heart compressions safely and effectively. A second objective is to, in parallel with the test equipment product development process, also perform an in-depth investigation on human chest biomechanics, especially related to CPR. The goal is to uncover biomechanical insights that could potentially be implemented in the test equipment, either directly or for future enhancements. This will be done through a literature search along with an exploratory analysis of two data sets with clinical data extracted from the LUCAS device.

1.2 Outline

This thesis project was divided into two distinct but interconnected parts - a **Biomechanical Analysis** and the **Development of Test Equipment** for the LUCAS device. The chronology was that these two parts were executed in parallel but with an alternating focus. The report will therefore naturally follow this separated workflow. Figure 2 illustrates this process and also how these to parts will intertwine and finally come together.

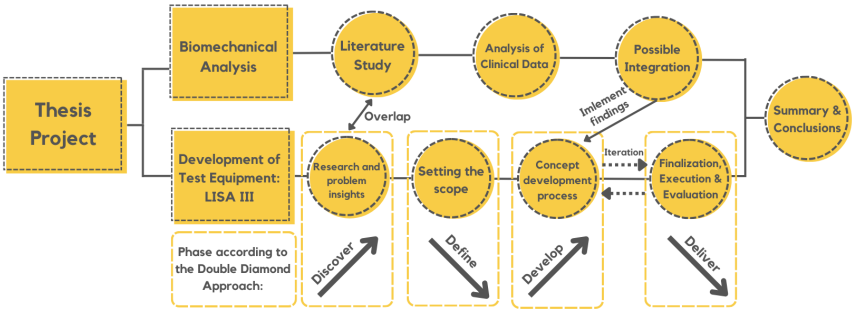


Figure 2: The project outline.

1.3 Work Distribution

Both parts have contributed equally to this master thesis project. The absolute majority of the work has been done together. This was important to enable the best possible solutions to emerge, as the ideation and concept generation benefits from team work. However, Malin took lead on the Biomechanical Analysis and Ester on the Product Development process. The report writing was mostly done separately, although with regular check-ins to ensure that the report is clear and easy to follow.

2 Background

This section of the report will cover theoretical background related to the project. Starting from the human anatomy, covering the thorax (chest), the functions of respiration (breathing) and the circulatory system (heart and blood flow). The focus will then shift to sudden cardiac arrest, cardiopulmonary resuscitation (CPR), mechanical CPR, the LUCAS Chest Compression System and finally its test equipment, where this master thesis project takes off.

2.1 The Anatomy and Physiology of the Human Chest

2.1.1 The Anatomy of the Thorax

First and foremost, in order to understand chest compressions, one must first understand basic anatomy related to the human chest, the thorax. Thorax is the term for the upper part of the torso, situated between the abdomen and neck - commonly referred to as the chest, see Figure 3. It consists of the respiratory system and heart, framed by the thoracic wall. The thoracic wall provides protection for the vital organs inside and has elastic properties through its connective tissue to enable respiratory movement. The thoracic wall consists of 24 ribs, 12 on each side of the spine. Furthermore, it includes sternum, the flat breastbone that anchors the rib structure in the center of the thoracic wall. Sternum is divided into three parts, manubrium, body and xiphoid process. The connection between sternum and the ribs is built up of costal cartilages on the front of the thorax and the connection on the back is to the spine, as can be seen in Figure 3 .

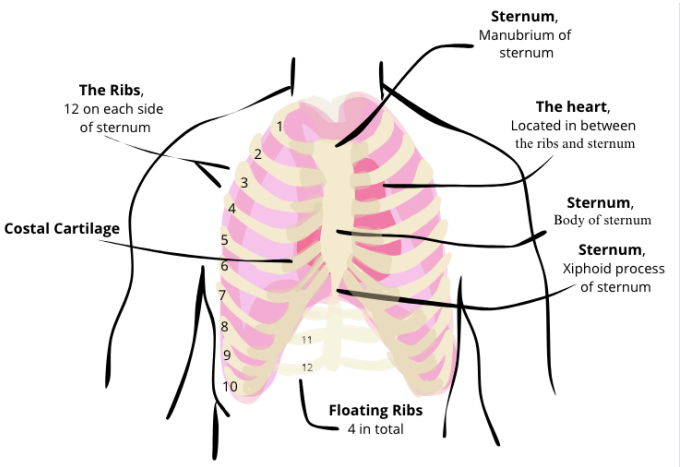


Figure 3: The skeletal construction of the thorax and anatomy of the chest in relation to the heart.

Moreover, the diaphragm and intercostal muscles enclose the system together with skin and fascia (connective tissue), see Figure 4. [1]

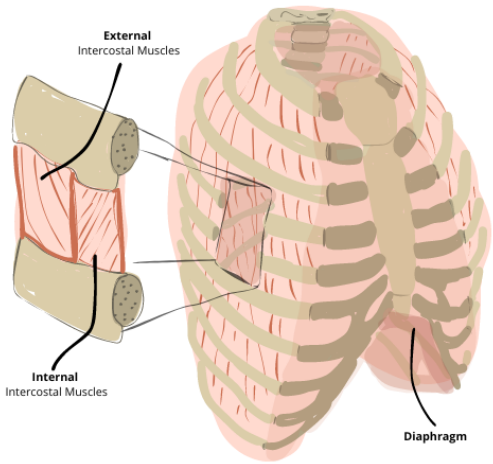


Figure 4: The internal and external intercostal muscles and diaphragm.

2.1.2 Circulation and Oxygenation

The human body is dependant on oxygen to function. There are three systems included in the process of providing oxygen. These are the respiratory, cardiovascular and nervous system. The respiratory system ensure supplying the body externally with oxygen and discard carbon dioxide and waste, through the respiratory organs. The cardiovascular system is in charge of circulating the oxygen-rich blood and providing the organs. Lastly, the nervous system acts as the chief in command, instructing the organs what to do. If one of these systems collapse and the body becomes deprived of oxygen, the organs will begin to fail and die. [2] Breathing is an active and somewhat passive process. It is divided into inspiration (breathing in) and exhalation (breathing out), whereas the last mentioned is a passive process. The inspiration commence by a contraction of the diaphragm and the intercostal muscles, located between the ribs. The outcome of the contraction is an increased chest volume due to the diaphragm lowering down towards the abdomen and the intercostal muscles lifts the rib cage. This action enables a pressure drop in the chest and air can reach the elastic lungs connected via connective tissue to the rib cage. The exhalation is consequential to the relaxation of the mentioned muscles and the air can move out.[2]

The cardiovascular system provides the body cells and organs with oxygen-rich blood and discards unwanted waste. The system is built up by the heart, blood and vessels (veins, arteries and capillaries). The vessels transport the blood out to and back from the body tissues, via the lungs, and possesses the capacity to control the blood flow. The arteries deliver oxygen and nutrient rich blood from the heart to

the organs whilst the veins return the by-products and oxygen-poor blood back to the heart. The capillaries are single cell branches from the arteries and they allow for the oxygen and nutrient exchange to the body tissues. There are two circulation systems in the body, the systemic and pulmonary circulation systems, see Figure 5. The pulmonary system is responsible for oxygenating the blood whilst the systemic ensure the blood reaches all the tissues. Without these systems functioning, organs and cells cannot receive oxygen and will therefore begin shut down. [3]

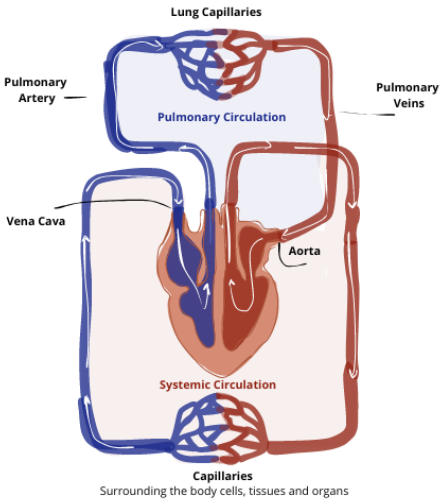


Figure 5: The heart, vessels and circulation systems.

2.1.3 Chest Height and Chest Stiffness

Two fundamental terms being investigated in this project is chest height and chest stiffness. The chest height measurement relevant for this project refers to the distance between the back plate of the LUCAS device and up to the chest of the patient. More precisely right above the lower part of sternum. Factors that may affect the chest height are sex, age and body mass index (BMI). However, every individual is different and there are many parameters to account for [4]. Regarding chest stiffness, it is according to the American Heart Association (AHA) defined as the maximum compression force (N) for each compression, divided by the compression depth (mm). Chest stiffness is measured in the unit N/mm. [5] Both chest height and stiffness are key elements for research on cardiopulmonary resuscitation, for example when determining compression depth and how large force to exert on the chest to adequately oxygenate the body.

2.2 Sudden Cardiac Arrest

Sudden cardiac arrest is a life threatening condition where the heart suddenly stops effectively beating, depriving the body and brain of oxygen-rich blood. The definition is a sudden loss of pulse, breathing and consciousness. Sudden cardiac arrest can be caused by several factors, including arrhythmia, blood clots in the lungs, severe blood loss, trauma, or excessive medication/drug intake. It is the third most common cause of death in Europe. [6]

There are two terms to distinguish in which setting a cardiac arrest has occurred, in-hospital cardiac arrest (IHCA) and out-of-hospital cardiac arrest (OHCA). The two settings come with different challenges and opportunities. This distinction is necessary to facilitate the creation of protocols and guidelines. Due to relevance to this thesis project, the main focus henceforth will be on OHCA and not IHCA, since this is mainly where the LUCAS operates. According to the European Resuscitation Council's (ERC) summary from 2021, the annual incidence of OHCA in Europe is somewhere between 67 to 170 per 100 000 inhabitants [7]. There are also sex disparities when it comes to incidence, where men are more likely to suffer an OHCA than women. A recent study from Germany showed that as high as 80% more men than women suffer from OHCA [8].

The outcome and survival of OHCA are dependent on several factors, reflected on the initial cause of the OHCA [6]. It is therefore difficult to say what exact factors have contributed or not to a certain outcome. The reality is however that the survival rates of sudden cardiac arrest remain low, with OHCA having particularly low rates of survival. Studies have consistently reported survival rates of approximately 7-8% when the cardiac arrests occur outside a hospital setting. The low survival rates are also what makes this a particularly difficult area to operate and study, since many factors play in and there are so few survivors. [9] [7]

2.3 Cardiopulmonary Resuscitation (CPR)

When a sudden cardiac arrest has occurred, it is crucial and time-sensitive to start CPR. CPR is an intervention aiming to maintain oxygenated blood flow to the vital organs while waiting for advanced medical care in a hospital facility. It involves two main parts: chest compressions and alternating ventilations, thus manually pumping the blood and oxygenating the body. The traditional way, CPR is conducted as follows: With the patient lying on their back, preferably on a hard surface, the person providing the CPR is positioned on their knees next to the patient's chest. The chest compressions are provided by putting two hands together on top och each other with straight arms and then pressing down 5-6 cm on the lower part of the patient's sternum, at a rate of 100-120 compressions per minute, see Figure 6. After 30 compressions, two ventilations (rescue breaths) are commonly given, however these can be excluded if the person is not trained in CPR or for any other reason can not provide rescue breaths. The critical factor is to continue providing uninterrupted compressions. It is important to note that CPR will not restart a heart, but merely maintain circulation and oxygenation of the body's vital organs until professional medical aid arrives. It should also be mentioned that alongside with CPR, common practise and recommendation is to also deliver shocks with an automated external defibrillator (AED), aiming to electrically defibrillate the heart

if it has a shockable rhythm. However, in this project, the focus will be on CPR, and defibrillations will not be further discussed. [6] Acceptable side effects from CPR should be the following according to The International Liaison Committee on Resuscitation (ILCOR): ”Rib fractures and other injuries are common but acceptable consequences of CPR given the alternative of death from cardiac arrest. After resuscitation, all patients should be reassessed and reevaluated for resuscitation-related injuries.” [10] Moreover, other reported side effects are skin tear, chest soreness and bruising [11].

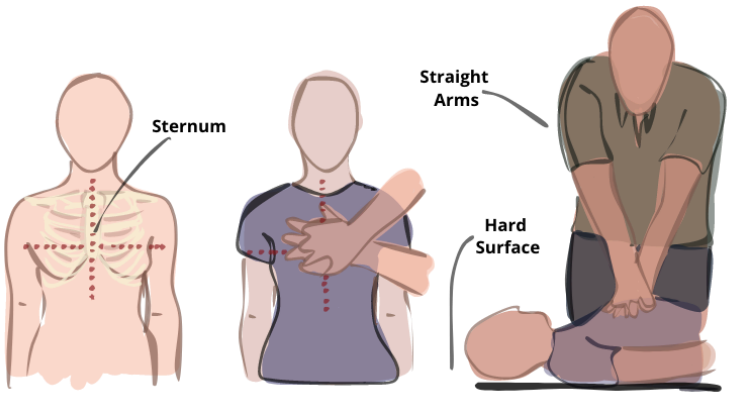


Figure 6: An illustration of a patient receiving CPR.

2.3.1 Current CPR Guidelines

The ERC are the ones providing guidelines for CPR in Europe. The guidelines for high quality CPR were updated in 2021 and are currently as follows:

- Start compressions as early as possible.
- Compress to a depth of 5-6 cm.
- Compress at the lower part of the sternum.
- Compress at a rate of 100-120 compressions per minute.
- Alternate 30 compressions with 2 ventilations.
- Allow the chest to completely recoil after each compression.
- Perform compressions at a hard surface, when possible. [6]

2.3.2 CPR Related Challenges in OHCA

As mentioned earlier, the outcomes for sudden cardiac arrest are grim and specifically for OHCA. While it is a serious condition, and not everyone can be saved, there is more to be done. CPR is the best option to keep patients alive, however, the quality of CPR, especially for OHCA, has been shown to be inadequate. A 2005

study by Wik et al., focusing on CPR quality, showed that chest compressions were not given half of the time and that the majority of compressions were too shallow [12]. This motivates the need to find new ways to efficiently and continuously provide high quality CPR. The fact that the quality of CPR in OHCA has been low is explained by that there are several factors and circumstance that add difficulty when the cardiac arrest has occurred out-of-hospital. For example, an untrained bystander will usually perform the initial CPR before trained personnel has arrived. Moreover, the transport to hospital complicates the delivery of high quality CPR, since the patient may need to be carried down staircases and then transported in and out of either ambulance or helicopter before they reach the hospital. These problems has been the main motivators behind the emergence of mechanical CPR solutions as an alternative to manual CPR. [12]

2.4 The Emergence of Mechanical CPR

Mechanical CPR refers to the use of automated systems or devices to provide mechanical chest compressions during resuscitation, developed to overcome limitations and difficulties associated to manual CPR. There exists different solutions within mechanical CPR. One option is to use a piston based system that exerts a load onto the patient's sternum to mimic traditional CPR. Another way is using a load distributing device based on bands wrapping around the body and squeezing the chest to manually provide blood flow [13]. There are also other CPR-related innovations that contributes to higher quality CPR, an example being automated external defibrillators (AED) with CPR feedback. These can have different designs but most are small and portable, and are placed between the patient's chest and the rescuer's hands. These devices include pressure sensors or accelerometers that can measure CPR quality (i.e. compression depth and rate) and give the user feedback prompts if the quality is not high enough. [14]

Focusing on mechanical CPR, the main benefits include higher consistency in terms of compression rate and sufficient compression depth, fewer interruptions and safer conditions for the rescue workers when transporting the patient to the hospital. It can also eliminate rescuer fatigue associated to manual CPR and allow the healthcare provider to conduct and focus on other life saving interventions. The main problem with manual CPR is difficulty reaching adequate compression depths. The guidelines say that the compressions should reach between 5-6 cm. They also clarify that potential rib fractures may occur but are an acceptable side effect necessary for survival. An untrained bystander will likely refrain from compressing to such depths due to the natural human fear of causing harm to another person. Even for trained personnel, the quality of CPR has been showed to be substandard. A study by Ødegaard et al. showed that 54% of trained personnel felt very uncomfortable with the idea of breaking ribs during CPR, and the authors hypothesized that this could be part of the reason that adequate depth is not reached. [15]

2.5 The LUCAS Chest Compression System

The LUCAS Chest Compression System is one of the leading solutions within mechanical CPR, delivering uniform, mechanically precise chest compressions to mimic CPR, in accordance with the American Heart Association (AHA) [2] and the European Resuscitation Council (ERC) guidelines [16].

The product was first under discussion in the 1990s, when a Norwegian paramedic, Willy Vistung, investigated ways of improving CPR. He then reached out to the M.D professor in Cardiothoracic surgery, Stig Steen in Lund. From there the product development of the Lund University Cardiopulmonary Assist System (LUCAS) continued, and has ascended to a preeminent position on a global scale in the domain of medical technology. The LUCAS device is today developed and manufactured by Stryker/Jolife AB, based in Lund, Sweden. [17] A drawing of the LUCAS device applied on a patient can be seen in Figure 7 below.

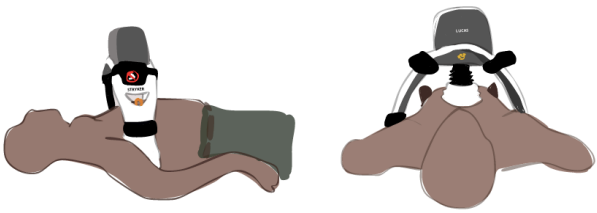


Figure 7: The LUCAS device, applied on a patient.

2.5.1 The LUCAS Device and Components

The latest version of LUCAS is the LUCAS 3, version 3.1. This third generation LUCAS was first made available in major markets in 2016. A visual of this device and its main components are presented in Figure 8 below.

1. **Carbon fiber back plate**
   To prevent movement of the patient due to soft surfaces underneath, which can result in compressions not reaching optimal compression depth.

2. **Hooking system**
   To connect the back plate with the rest of the system, for an easy mounting process.

3. **Stabilization strap**
   To ensure the patient is in a fixed position and avoid movement of LUCAS.

4. **Disposable suction cup**
   Placed to execute cyclic compression with three different rates; 102, 111 and 120 compressions per minute. Adjustable compression depth 45 to 53 ± 2mm.

5. **Release rings**
   To easily unhook the system from the back plate.

6. **Securing straps**
   Used to fix the arms for safety during transportation.

7. **Computer system and battery**
   A 45 minutes continuous run time. Software system to provide Comprehensive post-event analysis. WiFi-connection to provide reports post use.

8. **User interface and display**
   Allows for change of settings and receiving feedback instructions during ongoing CPR.

Figure 8: The LUCAS device, with components.

2.5.2 Intended Use and Contraindications

The product serves to perform external cardiac compressions on patients in adulthood suffering from sudden cardiac arrest. The LUCAS device is only recommended for use when it is not possible to receive effective high quality manual CPR performed by professionally trained personnel. Examples of these specific situations can be during transport, extended CPR, or just absence of trained personnel. The product should not be used if it cannot be safely and correctly positioned on the patient's chest. There are also dimensional limitations regarding chest height. If the chest height is too small, the LUCAS device will alarm, and can not be used. If the chest height is too large to fit the patient between the back plate and the piston, the hooking system will not be able to connect and the device can not be used. [11]

2.6 Test Equipment for the LUCAS Device

Testing and validating products and equipment is an important step in evaluating their function and effect. Especially for medical devices, it is essential that the devices function as they are intended to.

The LUCAS device has an internal testing system with built in sensors and a data collecting system that can measure the output of the device including, but not limited to compression force, depth and frequency. However, there remains a need to externally test, evaluate and validate the LUCAS device. A test equipment that can accurately measure the output of the LUCAS device is needed, both to be used by the development team at Stryker/Jolife AB and also externally to calibrate the function of LUCAS for example after it has undergone service. There exists a current solution, a test equipment going by the name LISA, (see Figure 9), that was manufactured to test the LUCAS in 2006. The LISA can measure and document output like compression force and depth from the LUCAS. However, this test equipment is not recently updated, not compliant with the new version of LUCAS and lacking in a few functions. To be more specific, LISA has a fixed set of springs connected to the compression plate, and thus a fixed chest stiffness. Moreover, the device can only test LUCAS at a restricted range of chest height.

Figure 9: LISA, the current test equipment for the LUCAS device.

2.7 Product Development Approach: The Double Diamond Method

The chosen theory for the product development process was the Double Diamond Method with an alternating diverge and converge approach. The method was initially conceived by the British Design Council and consists of a blueprint for product developers to implement when designing new products [18]. The approach is visual and simple to understand and builds on the idea of broadening one's perspective and thereafter narrowing it down to specify user needs and technical spec-

ifications for further implementations, to reach the desired end product. It conveys core principles that includes user centered design thinking, visual and inclusive communication and an overall iterative process. The model includes a clear visual representation and phases with well structured steps. A simple visual of this model can be seen in Figure 10 below.

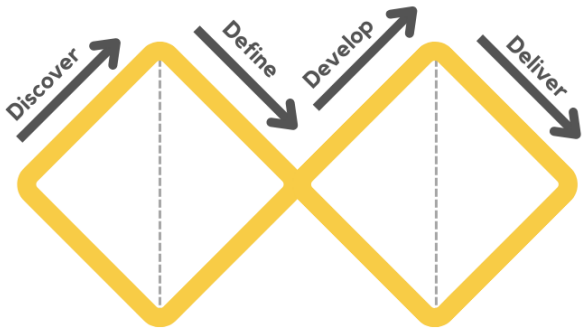


Figure 10: A visual representation of the Double Diamond Method.

The method constitutes four phases; Discover, Define, Develop and Deliver. The discovery phase sets the scene for the design process, by truly understanding the problem and gathering insights of the user needs. In the define step, the product specifications are set to create a framework for the project and make relevant constraints. The developing phase consists of concept creation and testing on different levels of complexity in order to devise a concept that fits all set requirements. Lastly, the deliver phase involves the construction of the physical product with desired materials. Furthermore, in each phase, tools used for the product development process were chosen based on the theory established by Ulrich and Eppinger in the book Product Design and Development [19]. Moreover, an evaluation of the final product is executed together with the users. This process is not a straight path and iterations are of importance throughout the process in order to reach the desired end product. [18]

2.8 Basic Mechanical Components and Theory

Some basic mechanics and theory used during the project will here be presented to provide a comprehensive background.

2.8.1 Springs and Calculating Spring Rates

A spring is a basic mechanic component that was present in many parts of this project and recurred in many concepts and iterations. The key characteristic of springs that made them such a crucial part of this project was their ability to provide consistent and variable resistance and stiffness. The spring's ability to store mechanical energy and provide elasticity and damping was crucial to the application in this project.

There are several types of springs, most common are compression springs and tension springs. The difference is that compression springs store energy when compressed and tension springs store energy when stretched. The combination of these make for a truly versatile and useful mechanical component. There are also a larger variety of other, more specialized springs. An example of such, is conical springs. Conical springs are cone shaped springs, with a non-linear force-displacement curve.

The spring rate is calculated using Hooke's law, seen in Equation (1) below. [20]

$$F = -kx \tag{1}$$

F is the applied force on the spring, measured in the unit newtons. X is the measured distance the spring has been compressed or stretched from its original equilibrium state, set to the unit meters. K is the spring constant and accounts for the relationship between the force and distance, stated in newtons per meter. There are several dimensional parameters that affect the spring constant.[20] A few examples of parameters that has been modified in this project when deciding on springs are wire diameter, inner and outer diameter, number of coils, free length, allowed compressed length and material, see Figure 11 below. [21]

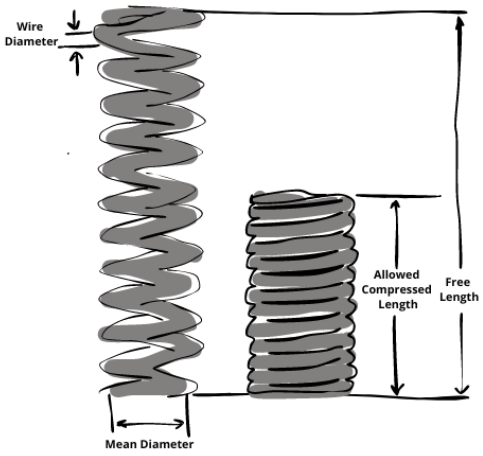


Figure 11: Parameters affecting the spring rate.

2.8.2 Stress, Strain and Young's Modulus

An important term in mechanics when determining whether a material will bend or break is the Young's Modulus (2). It is a measure for how a material will act in terms of deformation, measuring in the unit pascal (Pa). The equation for Young's Modulus can be seen below:

$$E = \frac{\sigma}{\varepsilon} \tag{2}$$

Where Stress (3) is

$$\sigma = \frac{F}{A} \tag{3}$$

and Strain (4) is

$$\varepsilon = \frac{dl}{l} \tag{4}$$

By using stress-strain curves, one can visualize how different materials will act when being subjected to a load. The Young's Modulus can be extracted from the stress-strain curve by measuring the slope of the initial, linear part of this curve. [22]

2.8.3 Fixed End Moments

The definition of moment is described as the effect unfolding when there is an applied force to a body, making it rotate around its axis. The moment is calculated using the applied force F multiplied with the moment arm d, see Equation (5). [23]

$$M = Fd \tag{5}$$

Fixed end moment is a term that was encountered during the building and developing of the test equipment. It is calculated with Equation (6) and (7) below, here both for one point loading and two, respectively. The structure is visualized in Figure 12 below.

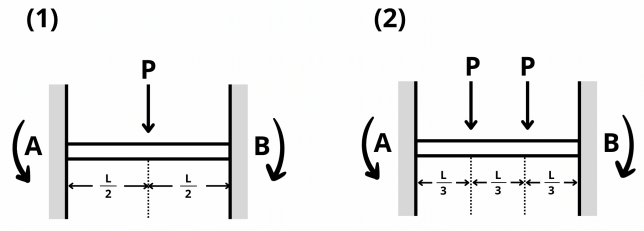


Figure 12: Fixed end moment for one and two point loading respectively. Related Equations (6) and (7) presented below.

$$(FEM)_{AB} = \frac{PL}{8} \tag{6}$$

$$(FEM)_{AB} = \frac{2PL}{9} \tag{7}$$

These calculations were used during the selection of components, further explained in section 6.1.2: The Height Adjustment.

3 Biomechanical Analysis

This section will explore biomechanics relevant and possible to implement in the LISA III test equipment for the LUCAS device. It will be divided into two parts: a literature study and a clinical data analysis.

3.1 Research Scope

The scope of this biomechanical analysis was set early on to limit the study and allow for it to realistically fit into the set time frame. The overall questions to be answered were: How does the chest respond to compressions and how do the chest's properties differ between individuals? To be more precise, three questions were formulated:

- *What factors affect chest height and what does the chest height distribution look like in LUCAS CPR patients?*
- *What factors affect chest stiffness and what does the chest stiffness distribution look like in LUCAS CPR patients?*
- *What does the force-depth relationship look like during CPR in humans?*

The selection of research questions was primarily driven by implementation possibilities for the LISA III test equipment and available factors within the data sets. Especially the second question was crucial for direct implementation in the development of LISA III.

3.2 Literature Study

To gain an understanding of the field and what has already been explored, a literature study was performed, focusing on chest biomechanics related to CPR. Key words used in search on Google Scholar were: CPR, Mechanical CPR, Chest Stiffness, Chest Biomechanics, Cardiopulmonary Resuscitation. The key words were searched both individually and in combination with the factors like sex and age.

3.2.1 Quality of Chest Compressions

The recommended compression depth for CPR is 5-6 cm according to guidelines by the ERC. A common problem for manual CPR, highlighted in the study by Abella et al., is that compressions are often too shallow. The study was a prospective observational study on IHCA from 2005, and explored the adherence to the CPR guidelines. It was concluded that 37.4% of compressions did not even reach 38 mm compression depth, which was set as a threshold for substandard quality [24]. This motivates the need for both further research and awareness on quality chest compressions. The stiffness of the chest and how it varies over individuals can contribute to difficulties reaching adequate compression depth.

3.2.2 The Effect of Chest Stiffness on CPR

A study by Tomlinson et al. concluded that there is a strong non-linear relationship between the compression force and achieved depth during chest compressions, with increased required force with compression depth. This was found by using a specially constructed sternal pad with an accelerometer and pressure sensor mounted on it, collecting results from 91 patients (61 men and 30 women) with OHCA in the northern Europe (Sweden, Norway and England).[25] A visualization of this non-linear relationship, taken from the study, can be seen below in Figure 13.

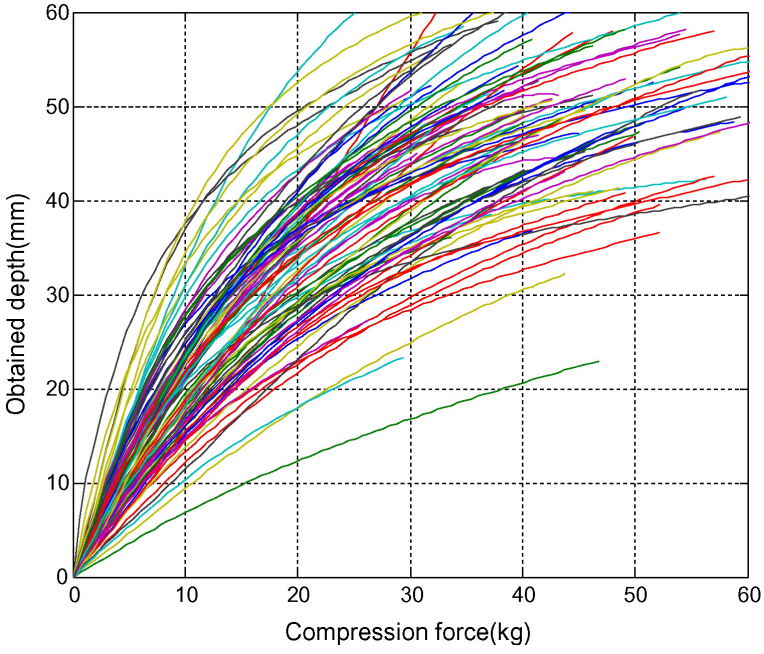


Figure 13: Force-depth curves generated in the study conducted by Tomlinson et al. [25]

As can be seen in the figure, there are significant differences between the 91 patients with a large distribution regarding the forces required for sternal displacement. The chest elasticity of the patients varied from 10 to 54 kg to reach 38 mm compression depth and this can, according to the authors, explain the variation. Furthermore, the different chest composition for men and women can affect the variation, where men have stiffer chests. [25]

Another finding was that chest stiffness significantly decreased over time. This is expected to be due to common CPR-related injuries such as fractures on either the ribs, the sternum or surrounding ligaments and tissue. The authors also found that the stiffness progressivity factor (i.e. the force required per mm) was higher for females than for males. [25]

3.2.3 Sex as a Factor in Chest Biomechanics

A study by Kimpara et al. approached chest stiffness from a different perspective, namely chest stiffness related to frontal and lateral impact in vehicle accidents. Even though impact on the chest from a vehicle accident is far from the lower and more cyclic load from CPR, some findings can still be of interest. This study focused on sex differences and aimed to find anatomical and biomechanical answers to why women have proved to be more vulnerable in vehicle accidents. The Kimpara study approached the question using two main methods: exploring cadaveric data from both frontal and lateral impacts as well as isolated rib bending tests. When comparing these results to impact from CPR, we are most interested in the results from frontal impact, not those from lateral impact. The results showed that the chest stiffness was significantly lower for women compared to men. It was hypothesized that this could be due to the smaller cross-sectional area of the women's ribs, which was also found in this study. The chest stiffness in women was 43% lower compared to men after frontal impact. The cross-sectional area of the ribs were 19% lower for women compared to men and the maximum bending force was also 30% lower. No difference in Young's modulus or bone mineral density could be found between men and women in this study. It was also found that the maximum deflection and compression ratio were significantly higher for women than for men when subjected to the same impact energy. [26] It should however again be noted that this might not translate directly to chest compressions, since the forces exerted are significantly different from those in this study.

3.2.4 The Impact of Age on Chest Biomechanics

A study from 2021 by Moriguchi et al., investigated risk factors related to serious injury induced by CPR [27]. The study included examining 74 patients, spanning over the years 2011 to 2018 and included a retrospective forensic autopsy, investigating injury risks associated with CPR. Specifically, the study investigated the thorax, aiming to distinguish how CPR affected the rib cage and organs. The measurement and magnitude for such injuries was measured using a scale called the Abbreviated Injury Scale (AIS). The patients were divided into those suffering from CPR-induced injuries and those who did not. The age mean value of the two groups were 67.8 versus 40.4 years. It was concluded that the only independent factor for the CPR-induced injuries was age.

Another study from 2013 conducted by Agnew et al. investigated rib stiffness related to age and the results showed that the stiffness changes significantly with age. The study was performed on 71 ribs extracted from 26 patients ranging from the ages 9 to 92. By analyzing the slope of the force-deflection curve, the stiffness could be obtained. The study revealed a trend of continuously increasing stiffness from childhood up to early adulthood, a flattening of the curve in parallel with reaching peak bone mass, and thereafter declining over increasing age.[28]

3.2.5 Summary and Conclusions

To summarize the findings from the literature study, there are several factors affecting the chest biomechanics that are of interest in relation to CPR. Firstly, the depth of chest compressions tend to not be reached in many CPR performances,

leading to lower CPR quality. Secondly, there were indications of a non-linear relationship between compression force and depth, pointing to the compositional structure of the chest. Since the compression force exponentially increased with the compression depth. Thirdly, when looking at sex differences, there were no direct indications of differences in Young's modulus nor bone density, when looking at isolated ribs. However, the cross-section of bones and overall dimensions were smaller for women, when examining the isolated ribs. There were also indications of lower chest stiffness for women as a result of frontal impact. Lastly, the impact of age on chest stiffness was clear with decreased stiffness over age.

3.3 Clinical Data Analysis

Besides researching already existing literature, this project also consisted of an analysis of clinical data with an exploratory approach. For this analysis, two data sets were utilized. Combined, these data sets encompasses 197 patients. Both data sets originates from the LUCAS device's internal measuring system. Summaries of the two data sets are presented in Figure 14 below.

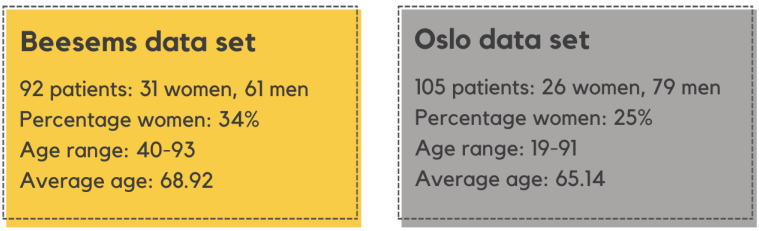


Figure 14: The two data sets used in the clinical data analysis.

3.3.1 The Beesems Data Set

The first data set was from the 2015 Study by Beesems et al. and will furthermore be referred to as the Beesems Data Set [29]. The available data includes patient-related information such as age, sex and chest height. It also includes technical data of compression force and compression depth at minute 1, 2, 3, 4 and 5. The initial age range encompassed individuals aged 14 to 93. However, given that the LUCAS device is designed specifically for adults, defined as 18 years of age and above, three patients falling below this age threshold were excluded. Consequently, the refined age range of the study participants became 40 to 93 years, with a total of 92 patients, consisting of 61 men and 31 women.

3.3.2 The Oslo Data Set

The second data set that was used originates from a recent study by Berve et al. that was conducted in collaboration with Stryker/Jolife AB [30]. It will henceforth be referred to as the Oslo data set, as the study was based in Oslo, Norway. This data set includes patient data (sex, age, weight, height, BMI, chest height) and technical data like chest compression time, compression depth and compression force. This data set includes 105 patients.

3.3.3 Statistical Tests and Methods

Since the data sets were given, no data gathering had to be done. The main focus for this project was to explore the data sets, visualize the data and look for insights and potential correlations. To visualize the data and perform statistical analyses, Microsoft Excel, Minitab and G*power was used. Both data sets were used for the chest height and stiffness ranges. However, for the subsequent analyses related to sex and age, only the Beesems data set was utilized.

Before any of the statistical tests, power analyses were conducted to determine the probability that a true effect is detected if it exists with the given sample size. The power analyses were conducted using the software G*Power. The results from these tests did however show that the sample sizes were actually too small for the set significance level of 0.05. However, the sample size of the data sets can not be changed, since it was already collected. Since the aim was to perform an exploratory analysis, the analysis was performed as planned.

Two main methods for statistical testing has been used. Firstly, when looking for correlations Pearson's Correlation Coefficient was used. Potential correlations were explored for both chest stiffness related to chest height, but also for chest stiffness and height related to age. For both cases, the null hypothesis was set to that there was no significant correlation. The significance level for all tests was set to 0.05. A two sample independent t-test was conducted for the comparison between women and men. The null hypothesis here was set to that there was no significant difference in chest height or stiffness for men and women. The tests were then performed using Minitab and the p-values were compared to the set significance levels. If the p-value was less or equal to the significance level, the null hypothesis was rejected and there was evidence of a true effect.

3.3.4 Results and Discussion

3.3.6.1 Chest Height

To begin, the chest height data only included patients fitting into the LUCAS device. Cardiac arrest patients who were either too large or too small for the LUCAS device were excluded, and there was no available data on the number of patients encompassed by this exclusion criteria. However, average values valuable for testing with the LISA III test equipment could be extracted. Below in Figure 15, is a visual representation of the chest height range with the data sets extracted from the Oslo and Beesems studies. Regarding the Beesems data set it was relatively evenly distributed within the range 191-271 mm, with its peak in the third subrange 211-231 mm. As for the Oslo data set it was more skewed to the lower chest heights with a majority within the range 171-231 mm. The most common chest height range was in the first subrange, with chest heights between 171-191 mm.

There was a large difference in the chest height span between these two data sets. Even though the patient data was extracted from relatively close geographic locations, they differ significantly.

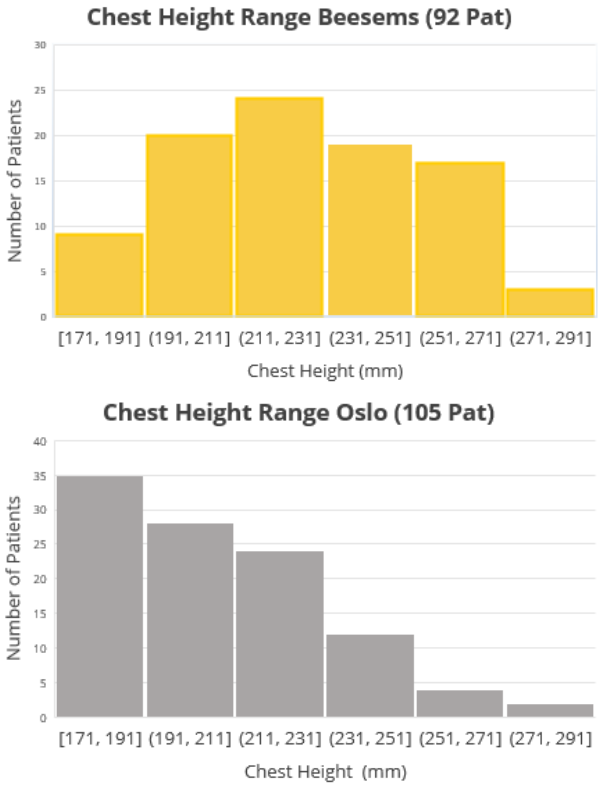


Figure 15: The distribution of patient chest heights from the Beesems and Oslo studies.

3.3.6.2 Chest Stiffness

The chest stiffness distributions from the two data sets are presented in Figure 16 below.

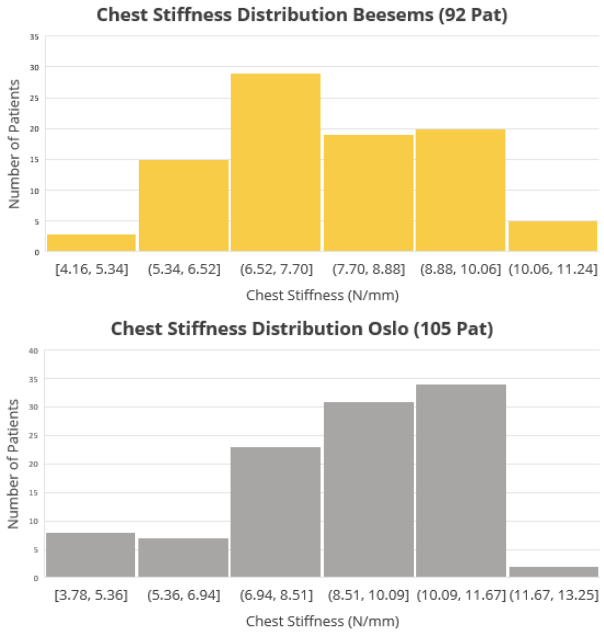


Figure 16: The distribution of chest stiffness. The first one is based on patient data from the Beesems study, whilst the second histogram is based on the Oslo study.

Similarly, there were clear differences between the two data sets in terms of chest stiffness. The patients in the Oslo study generally had stiffer chests than the ones in the Beesems study. To quantify this difference, the average chest stiffness for the patients in the Beesems study was 7.85 N/mm and for the patients in the Oslo study, this number was 8.98 N/mm. It was hypothesized that this difference in chest stiffness might be related to the previously found differences for these data sets in terms of chest height, and potentially that a small chest height would mean a higher chest stiffness. However, when this was explored within the two data sets, no clear correlation was found. The results are shown in Figure 17 below.

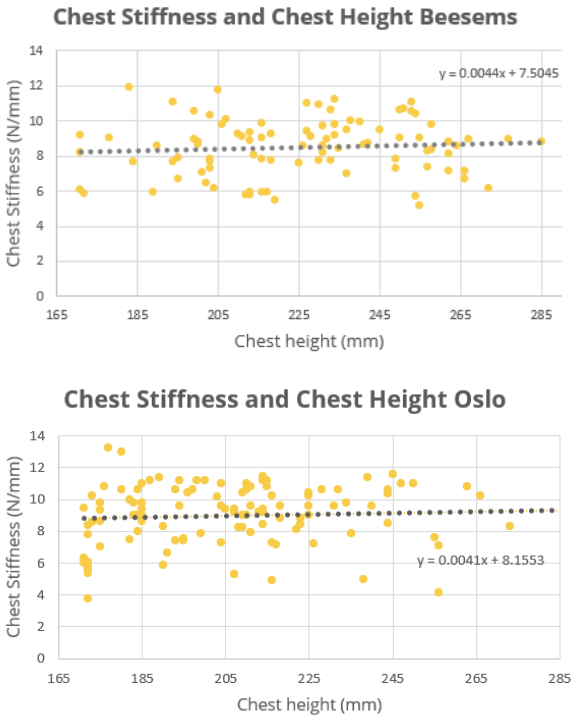


Figure 17: Chest stiffness over chest height within the Beesems and Oslo study respectively.

The Pearson' correlation coefficient was calculated for this potential correlation in both data sets separately and the results were as follows:

Beesems Data Set:

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
Chest Stiffness	Chest Height	92	0.075	(-0.132, 0.275)	0.479

Oslo Data Set:

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
Chest Stiffness	Chest Height	110	0.055	(-0.134, 0.240)	0.568

The Pearson's correlation coefficient was 0.075 for this potential correlation, with a p-value of 0.479. Since $0.479 > 0.05$, the null hypothesis can not be dismissed, meaning no statistically significant correlation between chest stiffness and chest height was found. However, as stated earlier, the sample size was too small so there was a possibility that a a true effect could have missed due to this.

3.3.6.3 Age-Related Variations

It was hypothesized, in relation to age, that both chest height and chest stiffness would decrease with age, due to natural anatomical processes related to aging. The results from the literature study also point to the chest biomechanics being altered due to aging. The visual results are presented in Figure 18 below.

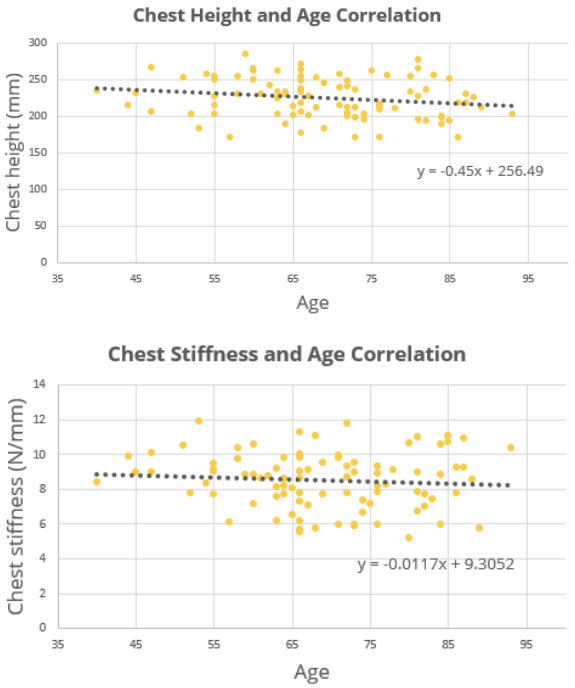


Figure 18: Differences in chest height and stiffness over age.

Pearson's correlation coefficients were calculated and the results were as follows:

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
Chest Stiffness	Age	92	-0.084	(-0.284, 0.123)	0.424
Chest Height	Age	92	-0.191	(-0.381, 0.014)	0.068

None of the p-values were smaller or equal to 0.05, and thus there were no statistically significant results. However, there seem to be some correlation between chest height and age that is stronger than that of chest stiffness and age.

3.3.6.4 Sex-Related Variations

Regarding sex-related correlations, it was hypothesized that both the chest height and stiffness would be lower for women than for men. The results are visualized in Figure 19 below.

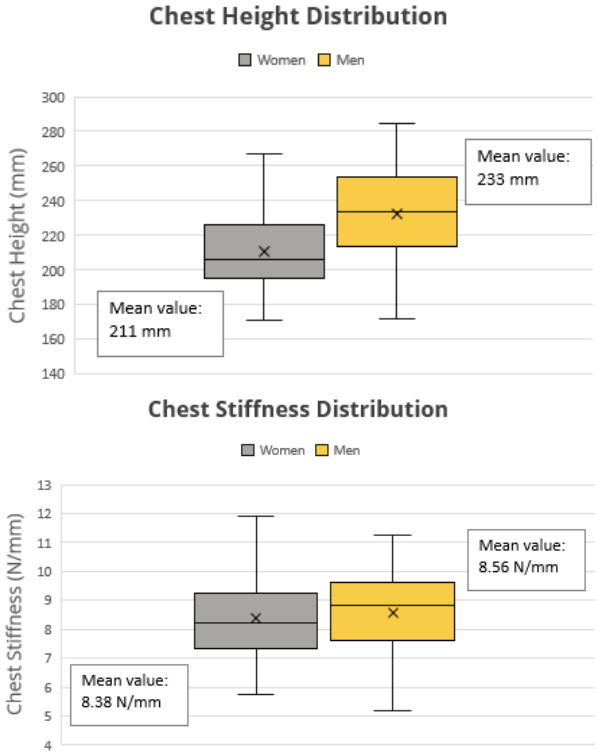


Figure 19: Differences in chest height and stiffness between women and men.

The visualized data show a trend that women tend to have smaller chest heights than men (mean value 211 mm and 233 mm respectively). Although, maybe more interestingly, women also appear to have, albeit slightly less stiff chests compared to men (mean value 8.38 N/mm and 8.56 N/mm), which is in line with what was found in the literature study.

The results from the two sample t-test were as follows:

Chest Height

Sample	N	Mean	StDev	SE Mean
Women	31	211.1	25.7	4.6
Men	61	232.8	24.8	3.2

T-Value	DF	P-Value
-3.88	58	0.000

Chest Stiffness

Sample	N	Mean	StDev	SE Mean
Women	31	8.38	1.71	0.31
Men	61	8.56	1.54	0.20

T-Value	DF	P-Value
-0.49	55	0.630

The results show that there is a statistically significant effect on chest height related to sex and that women have smaller chests than men. There was no statistically significant result for chest stiffness.

3.3.5 Summary of Clinical Data Analysis

A summary with average values for chest height and chest stiffness for the two data sets are presented in Table 1 below. These values answer the two first research questions and gives a range to use for the test equipment, based on real patient data.

Table 1: Summary Clinical Data Analysis Chest Height and Stiffness

Data Set	Average Chest Height (mm)	Average Chest Stiffness (N/mm)
Beesems	226	7.85
Oslo	207	8.98
Overall	216	8.42

To conclude, there were clear differences between the two data sets both in terms of chest height and chest stiffness. The Oslo data set showed smaller chest heights and higher chest stiffness levels. Trends in the data supporting our hypotheses could be detected when looking at correlations. Due to the low statistical power given the small sample size, a statistical significance was only detected for the correlation of chest height and sex.

A limitation was the geographic bias of the data sets. The Beesems data was collected in the North Holland region of the Netherlands and the Oslo data within Norway. These are relatively small areas and the results can therefore not be expected to represent the entire population. More diverse data collection could be beneficial for more representative results.

3.4 Discussion and Future Work

The chosen statistical tests were the two sample independent t-test and Pearson correlation. By choosing these tests, assumptions like normality and homogeneity of variances are assumed. For future work, these assumptions should be further assessed and if not achieved, non-parametric alternatives like the Mann-Whitney U-test and Spearman rank correlation could be chosen.

A finding in the analysis was that the data set that generally had smaller chests also generally had higher chest stiffness. However, when exploring this potential correlation with statistical methods, no statistical significant correlation was found, poossibly due to the small sample size. It remains an intriguing idea that could be further explored in future studies. It also sparks the question of what is actually the optimal compression depth. Does a smaller patient benefit from an equally deep compression as a patient with significantly larger chest size? As of today, all patients are compressed to the same depth, following international guidelines for CPR. It can be hypothesized that the higher stiffness for the smaller chest sizes are due to compression of deeper tissues with higher resistance since smaller patients receive deeper compressions relative to their chest size. This also prompts questions regarding sex differences and quality of CPR, since women generally have

smaller chest heights than men. Is CPR equally effective for both men and women when following the guidelines of compression depth?

For the development of the LISA III test equipment, it would be interesting to further explore a potential non-linear relationship between compression force and compression depth. However, to do this, another measurement technique than the internal system in the LUCAS will need to be used since this data is not available here. There are however earlier studies supporting this claim [25].

Another interesting point to further explore is the distribution of chest heights in a larger population, not just among those who fit into the LUCAS as in these data sets. It would be interesting to see what percentage of the population that actually fit into the LUCAS. This could be useful for further development of the LUCAS to include a larger range of possible patients. It could also give an indication on approximately how much larger or smaller it needs to be to include the largest number of additional patients, whilst also making necessary cut offs to keep the device realistic.

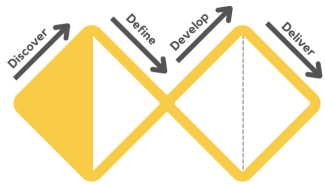
4 Development of Test Equipment - LISA III

This section covers the process of developing the test equipment, going by the name LISA III. The main theme for this part of the project has been trial, error and iteration.

4.1 Tools, Software and Methods

A large part of the project included creating a detailed CAD model of the new test equipment. This was carried out in the CAD and simulation software SolidWorks 2021 SP5.1. From an early stage, SolidWorks was utilized to realize quick concepts and being able to discard or encourage ideas directly. To test and evaluate the test equipment, the extension of this program, SolidWorks Simulation, was used to model how external forces affected the system. Another software, ANSYS Granta Edupack, was also used in a smaller scale to explore and learn more about materials related to the project. Physical prototypes were constructed in-house in the workshop at Stryker/Jolife AB. Available tools were: mill, drill, angle grinder, lathe and miscellaneous smaller tools.

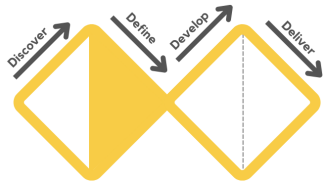
4.2 Discover: Research and Problem Insights



The discover phase of the Double Diamond method is the first diverging phase, where the goal is to thoroughly understand the problem.

This diverging phase commenced by understanding the question at issue, specifying the stakeholders and clarifying in what setting the product would be used. The test equipment is initially intended to be used for in-house testing and verification of the LUCAS device, ultimately ending up on relevant medical hubs worldwide. The stakeholders are Stryker/Jolife AB employees, service technicians and medical personnel. Furthermore, to understand every aspect of the problem, relevant research was made to get familiarized with concepts, mechanisms and the theory behind the LUCAS device that the test equipment will be built for. An introduction to the workshop was also crucial to see possibilities and limitations regarding material and component choices, costs and methods for the prototyping.

4.3 Define: Setting the Scope



The define phase of the Double Diamond method is the first converging phase with the aim to define the challenge.

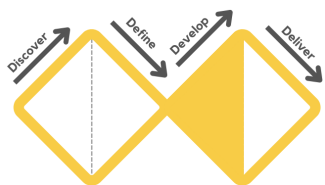
The main objective of this phase was to form the product specification to truly comprehend the user needs. The focus was on a converging approach where the findings from the previous phase were processed. In this case, Stryker/Jolife AB had issued a product specification with set requirements, the main requirements are presented in Table 2 below. This document acted as the base, to be merged with the research findings, and thus constitute the final specification.

Table 2: A simplified list of the main requirements for LISA III System.

Functions	LISA III Requirements
Main Functionality	Shall measure and document compression force, depth, time, ratio and frequency
Dimensions	The dimension of the system shall be maximum 1000x550x500 mm
	The weight of the system shall be maximum 20 kg
Components	Shall be built on standard components to the highest extent possible
Adjustability	Shall be adjustable in terms of chest height and stiffness
Compatibility	Shall be compatible with current and future versions of LUCAS

One dimension of the project was centered around the preference that the final product should be constructed in-house with the available tools and materials and off-the-shelf components. This limitation had to be taken into consideration throughout the following phases of the product development process, for example regarding costs and lead times.

4.4 Develop: The Concept Development Process



The develop phase of the Double Diamond method is the second diverging stage where ideas and solutions are generated and evaluated.

4.4.1 Phase 1: Design Sprint

The initial step of the developing phase included a formulation of the execution plan for the idea generation. This was carried out using tools provided by the design sprint [31], which is a step by step methodology with the same diverge-converge approach as Double Diamond. *'The Comparable Problem Method'* embarked this segment, by conducting a market research and benchmarking and thus delving into mechanisms found in other fields similar to the desired product and explore competitors. The next tool named *'How might we?' (HMW)*, rephrased the problem

statement with a focus on the opportunities within each subproblem set by the product specification. As a complement to HMW, *'The Boot Up Note Taking'* tool was presented, to be well prepared for the first prototype sketching step. By reviewing all the findings from previous steps and writing down potential ideas, it worked as a stepping stone into the next stage: the concept sketching. To initiate the concept sketching, the *'Crazy 8's'* was utilized. With a time frame of eight minutes, one was instructed to individually sketch eight different concepts, with no limitations to what it should include. Thereafter, the concepts were presented and discussed to remove possible unwanted and unrealistic ideas. A few ideas generated in this step can be seen in Figure 20.

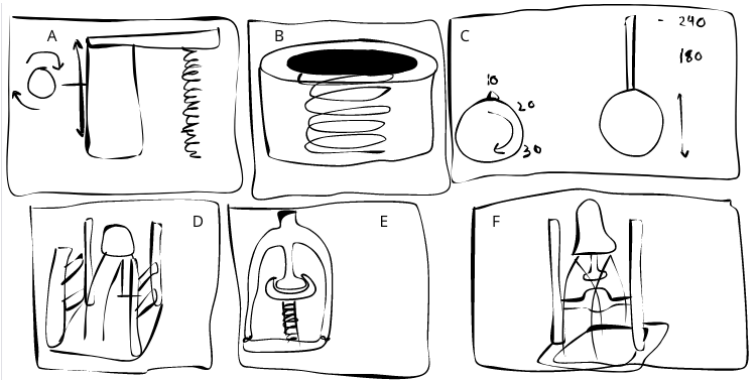


Figure 20: The outcome of crazy 8's with idea. A: An adjustable chest stiffness B: The springs in a changeable cylindrical module C: explicit and separated ways to change stiffness and height D: A four pillar structure for robustness E: A claw attached to the piston F:A two pillar solution with horizontal axis

The following stage included more in-depth sketching using the *'Solution Sketch'* technique. Instead of exploring several concepts, one concept at a time and its potential substructures was explored. The goal was to easier explain and visualize the concepts that could be of interest. In total, three sketches each were to be conducted, with a time frame of 20 minutes for each sketch.

4.4.2 Phase 2: Concept Decomposition and Iteration

The method *'Concept Decomposition'* aiming to decompose a complex problem into smaller subproblems, presented by Ulrich and Eppinger, was used to facilitate the development process [19]. Since the requirements set for the system were complex with several dimensions to take into consideration, it was advantageous to apply this tool. The initial step started by viewing the problems as one black box, focusing on how it operates, and thus understanding the overall properties. Thereafter parts were identified, on a conceptual level, in the structure and their function was described. This breakdown was executed until it was simple enough to visualize and thus conceptualize each part. [19] After the concept decomposition application, four main subproblems were identified to form the test equipment. They consisted of the main structure, back plate integration, height adjustment and

stiffness adjustment. Within each subproblem, themes were identified upon which the concepts could be classified by. Furthermore, a separated fifth subproblem was formed, the biomechanical implementations, to keep in mind different ways to implement findings from the biomechanical analysis in the test equipment.

4.4.3 Phase 3: Idea Generation

Thereafter, a new session of idea generation commenced with a diverging approach to find subconcepts to each subproblem. This part of the process focused on developing the concepts generated in Phase 1 and categorize them by their subproblem, as can be seen in the problem decomposition tree with its subproblems and ideas in Figure 21.

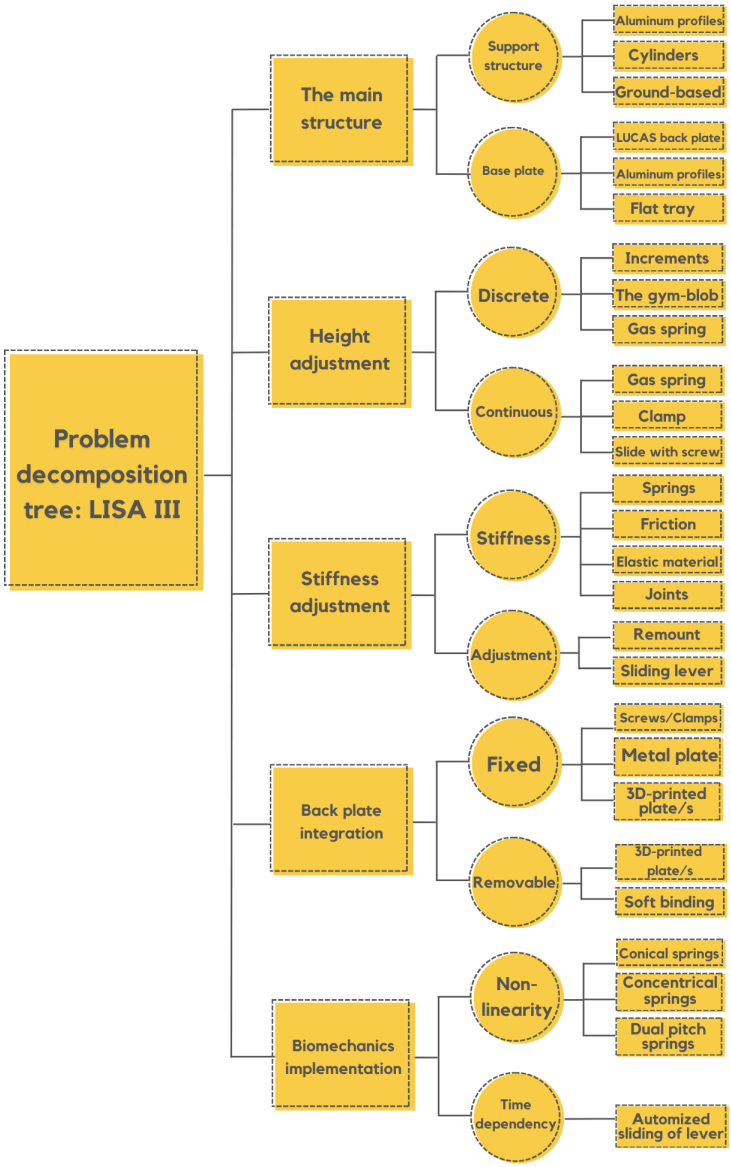
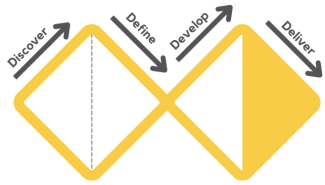


Figure 21: A problem decomposition tree: Division by the subproblems with devised concepts for each subproblem.

4.5 Deliver: Finalization, Execution and Evaluation



The deliver phase of the Double Diamond method is the second converging method and the last step of the whole process, this is where testing and assessment of the solutions come in.

In the development phase, four distinct subproblems and one separate consideration were extracted, as mentioned before, using the problem decomposition method. Early solutions and prototypes will here be presented by division into those following four subproblems together with their respective *How might we?* problem statement, as described in 4.4.1. The subproblems are, as stated above: The main structure, Height adjustment, Adjustable chest stiffness module and Back plate integration and attachment.

4.5.1 The Main Structure

How might we construct the main structure in a robust way, and with mainly off-the-shelf components?

This first subproblem was highly dependent on the solutions emerging from the other subproblems, however it was a challenging task that was bounded by a number of requirements. At the start of the project it was established that the test equipment was preferably to be constructed with off-the-shelf components that can be assembled in-house. There were also requirements in terms of dimensions and weight that gave a framework to work with in the developing process. The full test equipment was not to exceed 1000x550x500 mm and 20 kg of weight. For this task, benchmarking was done, and to contrast, out-of-the-box thinking was encouraged to construct a viable main structure for the test equipment.

In an early stage of the process, the idea to use aluminum profiles emerged and several concepts for the construction using these were formed. To allow for the height adjustment system, it was clear early on that a suitable option for the structure could be a two pillar solution. A significant challenge was however how to build it to endure torque. A common component when constructing test equipment and rough prototypes are aluminum profiles, due to their flexibility and ease to move them around with connecting elements. Furthermore, the material is lightweight and suitable for many different applications since there are many standard components that are compatible with the aluminum profiles. Throughout the project, the two profile system went through a few changes in terms of choice of width and height of the structure and the dimensions of the profiles. It was also desirable to trim off excess material to really tighten up the structure, but at the same time retain the robustness. An outcome of concepts developed in this stage can be seen in Figure 22 below.

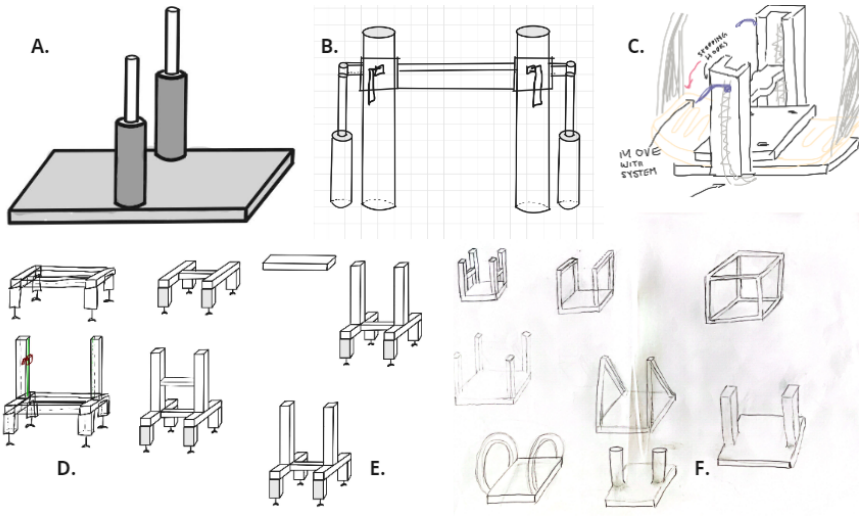


Figure 22: An extract from the idea generation for the main structure. A and B: Using two gas springs either by themselves or with a guiding pole. The structure standing on a metallic platform. C: A two pillar solution on a metal platform. D: A square solid foundation with two pillars, standing on four legs. E: A foundation formed as the letter H. F: An early out of the box sketching session to visualize and investigate in all kinds of structures.

4.5.2 The Height Adjustment

How might we implement a height adjustment that is exact and securely fixed, in a range from 140 to 340 mm?

The main challenge for this subproblem was assuring a stable enough fixation at different heights within the given range while also creating enough space for this range to be plausible. Considering the given large chest height range for the LUCAS device to operate on, it added complexity regarding dimensions for the new test equipment. Furthermore, the LUCAS device had to be fully assembled with the back plate, so LISA III needed to conform to these dimensions. Another challenge was ensuring that, if the height adjustment was attached to two or more profiles, it must be synchronous so that it remained level.

Another aspect under consideration was whether or not the height adjustment should be in discrete increments or continuous. There were many advantages with discrete increments, for example that the inter-measurement repeatability would be precise. However, many off-the-shelf components that were explored came with continuous adjustment possibilities. Inspiration was found both in other mechanical constructions like automation devices and 3D-printer construction but also in our everyday life, for example in gym equipment, standing desks and office chairs. Some early sketches and ideas are presented in Figure 23 below.

Concepts that emerged was for example for the height adjustment to be based on gas springs (the type of spring used to adjust height in office chairs). This

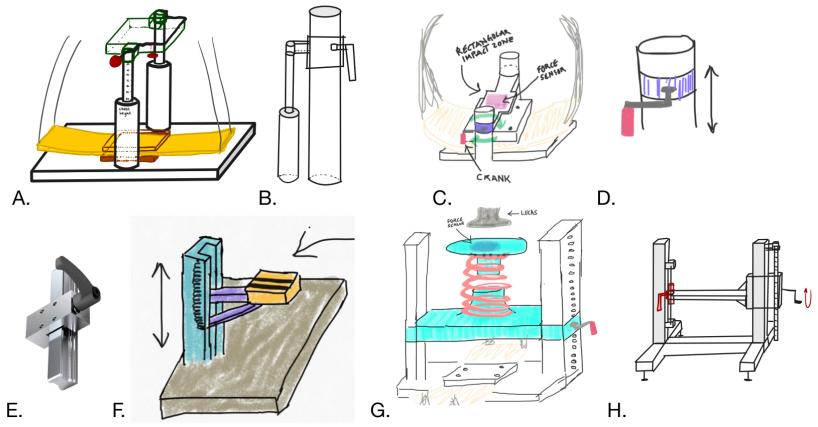


Figure 23: Solution sketches for height adjustment. A, B, F: Using gas springs. C, D: Using cranks. E. Manual clamping element. G: Discrete manual height adjustment. H: Combination of clamp and crank solution.

idea was favored due to the fact that it, except for the ability ot adjust the height, also provides an extra feature - being able to aid the user with lifting. The main limitation was finding off-the-shelf gas springs with large enough travel range and at the same time small enough in compressed state.

Inspired by other automation devices and other mechanical constructions, linear guides together with clamps were considered as an option for the height adjustment. These modules exist off-the-shelf and is a reliable option since it has been used in similar applications. There are high requirements on these clamps as they must be able to withstands the force exerted by the LUCAS device on the test system. A challenge for the linear guide option was that their intended use did not include being mounted facing each other with a horizontal aluminum profile connected in between. Ultimately imposing high demand on synchronization and withstanding the torque. This problem was solved by manufacturing specially made connecting plates to ensure a robust connection to the horizontal profile and the stiffness module. To withstand the torque, the selection and dimensions of both the linear guide and rails were essential. The linear guides would have to be carefully chosen to have clearance for the force ranges they would have to endure. To ensure synchronization and correct placement of the linear guides, additional length would need to added to the base aluminum profile. This way, there is some extra ”wiggle room” when mounting the vertical profiles to ensure that the guides run smoothly and synchronized.

4.5.3 The Stiffness Module

How might we integrate an adjustable stiffness module that closely mimics human chest biomechanics?

The challenge here was finding ways to make the chest stiffness adjustable in a reasonably easy way. While benchmarking and exploring other solutions to mimic a human chest for CPR training, several companies had interesting products. The Norwegian company Laerdal medical and the Danish company Ambu both produce manikins for CPR training. Even though this project is not aiming to construct a CPR manikin, the technique used here was of interest as the main challenge remain the same - how can we create a device or manikin that mimics a human chest? Laerdal Medical solved the need to adjust chest stiffness on their manikins in the most simple way - by allowing the user to easily open up and disassemble and assemble a new spring. This would be the most straight forward way to do it also for this test equipment, but there were some disadvantages with this solution, mainly the fear of loose parts to be lost.

The Danish company Ambu had another interesting solution for adjustable stiffness [32]. A sliding lever system with two springs allow their manikin to be adjusted between three increments of chest stiffness, without disassembling it at all. A sketch of this concept can be seen in Figure 24. Due to the construction complexity and space limitations, this concept was not further explored even though it was an intriguing solution on easy alteration between different chest stiffness levels.

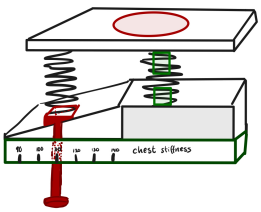


Figure 24: Sketch of the sliding lever system.

A possible solution that was explored was the use of alternative materials to replace where springs would ordinarily be used to represent the chest stiffness in the test equipment. Different types of elastic materials were considered and experts and industry representatives consulted on the matter. On the first iteration, the idea was to use materials like rubbers, silicone, plastic or foams. At a later stage, options like damping pads, thermoplastics, moulded silicone structures and other air-filled structures emerged. Elastic materials are useful in applications where there are space limitations. They have their own damping and their resilience make the material easily returning to its original state. Elastic materials such as polyethylene operates much like springs and are therefore suitable for a spring-like application. The materials selection software ANSYS Granta Edupack was used to explore what materials could be relevant for our application. Ashby plots were created for this purpose and to visualize the options for materials selection, see Figure 25 below. Vickers hardness is plotted against fatigue strength, since compression tests related to Vickers are common for soft and foam-like materials [33]. The fatigue strength is interesting since a material that can endure cyclic loading is needed. The ideal material would be in the bottom right corner of this plot.

The challenge with alternative elastic materials became more evident here, since the requirements is an elastic or soft material that can endure long cyclic loading, which few materials can live up to. However, foams (bright green, marked in the plot) were considered to be the best solution. Also polyurethane (marked in

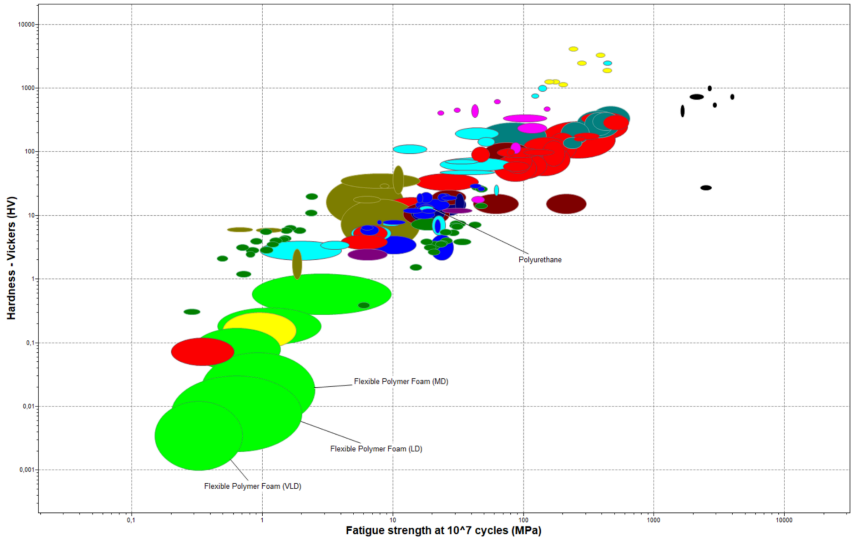


Figure 25: Ashby plot for Vickers Hardness vs Fatigue Strength at 10^7 cycles.

plot), was further considered in this process. In this project we chose to not proceed with the alternative material investigation due to the time constraints.

Another challenge regarding the stiffness module was that it should provide resistance in both compression and decompression, which mechanically results in a more complex structure. Ideas to satisfy this are presented in Figure 26 below.

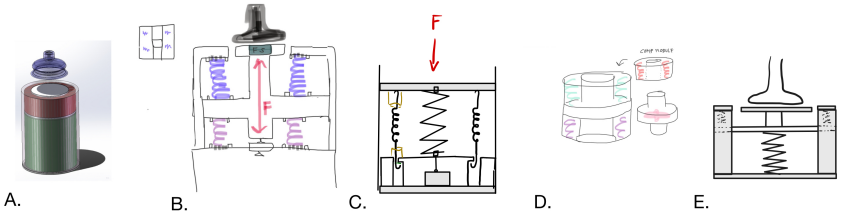


Figure 26: Solution sketches for compression and decompression stiffness module. A: Using elastic materials. C: Tension and compression spring module. B, D, E: Compression spring combinations.

As mentioned earlier, the aim to make the stiffness adjustable proved to be particularly challenging, especially when taking into account the space limitations. This was because the back plate integration, the height adjustment system and resistance had to be present both in compression and decompression. Different concepts were explored and early sketches are presented in Figure 27 below.

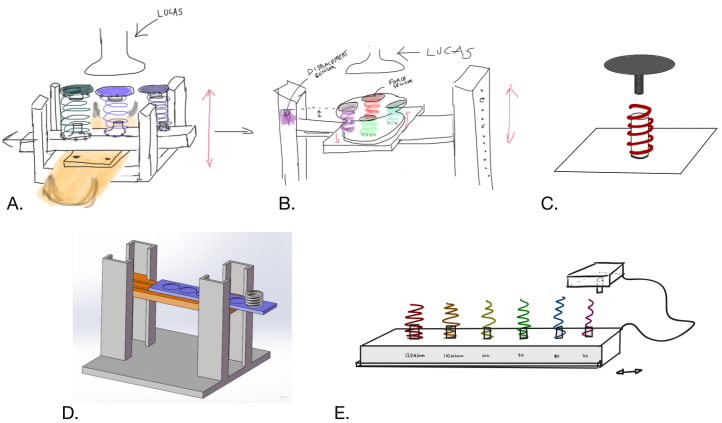


Figure 27: Solution sketches for adjustment of the stiffness module. A, D, E: Horizontal slide to adjust. B: Circular twist adjustment. C: Simple spring exchange.

Finally, a promising concept for providing resistance both in compression and decompression emerged. At this early stage of the development of LISA III, it was decided that it was more important to give a proof of concept and a first prototype of LISA III with this new concept than having it fully adjustable. Thus this first prototype would not be made adjustable in terms of stiffness. This new concept for the stiffness module was named the Spring-in-Spring solution and combines a compression spring with a concentrically placed tension spring. This concept is presented more thoroughly in Final Concepts, The Stiffness Module 6.1.3.

4.5.4 The Back Plate Attachment

How might we make space for, and secure the back plate, in a way that realistically mimics how it would be fixed by the weight of a human patient?

The main challenge for the back plate attachment was fixing the back plate but yet allowing it to deform in the same way as is would naturally when it is used on a patient. Thus it was explored how tight this fixation should be and also how to not over-complicate this component of the test equipment. First, a 3D-printed double sided-fixation approach was explored, see Figure 28. It was constructed to be the approximate size of a human back when laying on the LUCAS back plate.

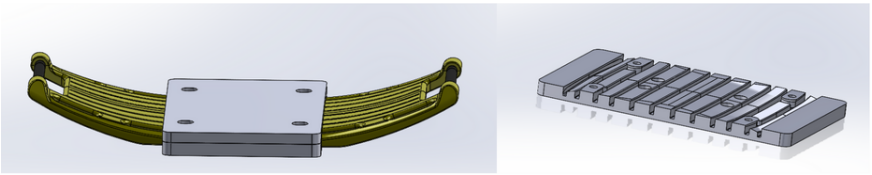


Figure 28: First generation Back plate attachment, left: full structure, right: lower side.

Further iterations aimed to simplify this solution as this first solution was considered to be too large and would be complex to manufacture as it would not fit into the 3D-printer. A second generation was then modeled, see Figure 29, where changes include a smaller size and only one-sided construction where the back plate connects directly to the aluminum profile on the underside.

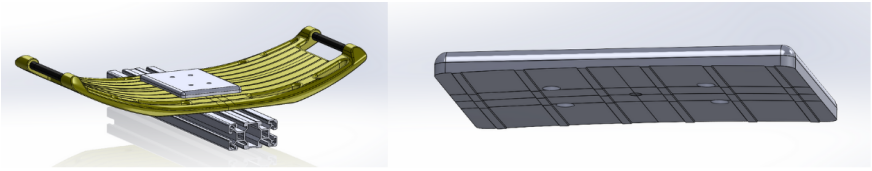


Figure 29: Second generation back plate attachment, left: full structure, right: only top.

When further researching the LUCAS back plate and how it deforms, it was uncovered that to allow for more natural flexion of the back plate, it would demand that the solid attachment point is smaller. Thus a third generation back plate began to be formed. This smaller width can be motivated as it aims to mimic the width of the most solid part of the back that compresses down on the back plate, namely the spine. The spine's approximate width that would be in contact with the back plate is 25 mm, and this is therefore the width of the new, third generation back plate attachment. This final version is presented in Final Concepts, Back plate Attachment 6.1.4 below.

4.5.5 Sensor Selection

While the goal of this project is to provide a model of, and build a rough functional prototype, sensors were not primary focus as a delimitation to fit the project into the fixed, 20-week time frame. However, within the scope of this project was to explore, select and make place for sensors that could be implemented in the future.

For the new test equipment, two primary types of sensors were required: a force sensor measuring both compression and tensile force, along with a distance measuring sensor. The first will measure the compression and decompression force that the LUCAS outputs. The latter will measure the compression depth and also log the chest height that the LUCAS is testing on.

Given by the requirements for the LISA III system was some approximate accuracies needed in the sensors, see Table 3.

Table 3: Accuracies and required measuring ranges for sensors. *cpm = compressions per minute.

Sensor Measurement	Range	Accuracy
Force	-200-1200 N	(±) 2%
Depth	150 mm	(±) 0.2 mm
Frequency	72-180 cpm*	(±) 2 cpm
Ratio	20-80 %	(±) 2 %
Time up and down	0.05-0.5 s	(±) 0.01 s

The main challenge for the sensor selection was finding a small enough load sensor to place it directly on the impact plate and coming up with solutions to either avoid or handle cords from the sensors if placed on the moving parts of the LISA III system. Also, the placement of the sensors were very dependent on the chosen concept for the stiffness module.

The most straight forward approach, in terms of ease of measurement, would be to place the sensors on the moving parts of the LISA III system. The most evident force sensor placement would be straight underneath the suction cup, incorporated in the impact plate. However, this would lead to additional problems with how to draw the cords to keep them from wearing and possible damage or even disrupting the movement initiated by the LUCAS device. Therefore, this option was discarded for the positioning. Other placements of the force sensor could be either down on the back plate fixation since it was hypothesized that the same forces that would act on the impact plate also would be present there. However, it remained uncertain if all the forces generated by the LUCAS device would be able to be measured in that position, with risk for decreased accuracy in the measurement.

Another possible position was placing the force sensors in connection with the springs, thus decreasing the dimensional limitations of the sensor. This solution would however increase the number of sensors needed.

Since the Spring-in-Spring concept turned out to be best suited for LISA III, two force measuring sensors were needed. These could be placed underneath each spring assembly, measuring both compression and tensile force. Since the new concept liberated additional space, it was no longer as crucial to go for the thinnest

sensor possible. However, the sensor still had to be relatively small and compact with the wanted accuracy, as listed in Table 2.

The integration of the distance measuring sensor was not as complex as with the force sensor. This sensor could be placed exterior to the most crucial components. There were several options to choose from regarding this type of distance measuring sensor. Some alternatives were ToF (Time of Flight), optical light, infrared and wire. After thoroughly investigating possible alternatives based on measurement accuracy as the main determinant, it was clear that a strong candidate would be high precision laser sensors. More precisely a triangulation laser sensor with RS422 interface as a standard, with an analog output. A triangulation laser operates by projecting a laser beam against a surface. By measuring the angle and the reflection time, the sensor can accurately measure the distance between the two objects. The RS422 interface is a serial data transmission standard to ensure improved noise immunity and allow the handling of high speed data communication over long distances. However since the distances we were operating with were not particularly long, it was still a valid alternative due to the high precision and tolerance for vibrations in the system. Due to the cost of this type of sensor and for the conceptual level of the prototype, conditions were not conducive to proceed and order the components. A much cheaper alternative would be wire sensors. However due to the high frequency of the compressions, those would wear out and are thus not suitable for the long-term use. Due to the time limit of the project, the choice of sensors were left on hold, and are to be taken into consideration for future versions of the test equipment. The same can be said for the force sensors. However, they need to be taken more into consideration for the concept since the dimensions are more crucial. More detailed description of the force sensors can be found in section 6.1.3.

4.5.6 Sourcing Components and Ordering Parts

Several different suppliers were considered for the components and parts for the LISA III test equipment. An important factor was minimizing lead times which resulted in using only Swedish suppliers. The aluminum profiles and fastening brackets were ordered from a Swedish partner to Bosch Rexroth [34], Logicsystem Pneumatik AB [35]. Height adjustment elements were PMI Motion Systems, ordered from the Swedish supplier Aluflex [36] and springs were ordered from Lesjöfors [21].

4.5.7 Building the Physical Prototype

The aim of this project was to have a rough functioning prototype and a proof of concept for the LISA III. With this is mind, not all components used for the construction were the ones meant for the final implementation. For example, the springs are prototype versions found in the Lesjöfors standard assortment, similar to the intended, customized ones. The force sensors are replicated and machined from an aluminum rod instead of purchasing the real ones. Several components that should be machined are 3D printed to save time and prototype quicker for this first version.

The 3D-printing software Z-Suite together with a Zortrax M300 3D-printer

were used for these early prototype components. Three separate batches were printed with several components. All were printed solid in Z-ULTRAT, a thermoplastic filament commonly used for 3D-printing. The material possess properties that are compatible with the technology of injection molding, suitable for mechanical parts when prototyping. It is one of the 3D-printing materials with highest strength, which makes it a good choice for functional prototypes, it is however not as strong as aluminum. The first batch of 3D-printed components can be seen, as they are just about to be finished, in Figure 30 below. The total print time for these components was just under 82 hours, the second batch took 122 hours and the last one 22 minutes.

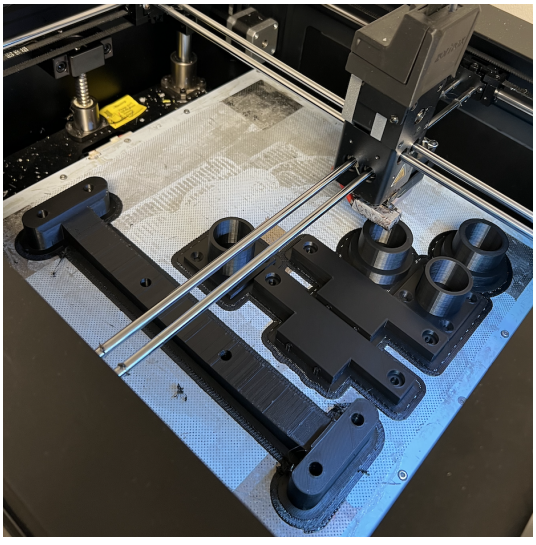


Figure 30: The first batch of 3D printed components.

Several parts were machined in the in-house workshop. The main tools used were the mill and the lathe. Most machined components were made out of scrap parts that was available in-house. The material used was aluminum due to availability, price, weight and ease of machining. Some modifications to purchased components were also made in the workshop. This includes widening of premade holes to fit the application, drilling and threading holes in shafts and cutting tension springs to correct length using an angle grinder.

5 Intermediate Solutions and Simulations - LISA III

This section will present the last steps of the development process before the final results are revealed in the following chapter. More specifically, presented here are evaluation methods and some intermediate concepts that were not proceeded with, but are still of interest to understand the full journey.

5.1 Concept Evaluation

At several points during the process, decisions on which concepts to proceed with had to be made. To refrain from making hasty decisions and keeping them information-based, concept evaluation matrices (CEM) were used as a decision making tool. This way, several concepts were compared fairly and more unbiased. A scoring system was constructed based on performance factors important for success of the concept, weighted by each factors relative importance. All scores where then summarized for each concept and finally, conclusions based on objective factors could be drawn. This way, we could exclude concepts that were initially favorites, but proved to be unrealistic based on these performance factors. Subconcepts that were evaluated this way were the height adjustment system, stiffness module and spring attachment solution. Examples of the performance factors were: price, weight, stability, simplicity, usability and more specific ones for each subproblem, for example synchronization and adjustment range for the height adjustment concept evaluation. To get an understanding of the process, a small extract from one of the CEMs can be seen in Figure 31 below. The rest of the CEMs can be found in the Appendix.

Criteria	Weighing (1-5)	Concept 1: Side single wheeler	Concept 2: 3d-printer screw with guide with clamp	Concept 3: 2 profile screw chain linked height adjustment	Concept 4: Gas spring as lift support, clamps	Concept 5: Connected gas spring height
						
Total		172	211	173	169	138

Figure 31: The concept evaluation matrix on the chest height concepts, scored according to different parameters.

Another effective way to evaluate concepts was including expert opinions. Besides regular check-ins with our supervisors, we also scheduled meetings with several experts within various topics, for example sensors, mechanical components and material selection. This was immensely helpful to reach the best possible solutions.

5.2 Intermediate Prototypes

Several intermediate prototypes and concepts emerged and were considered at different points in the process. Several promising concepts that did not progress to the final development stages will be presented here.

5.2.1 The Conical Spring Concept

The idea to use conical springs in the stiffness module was an early concept, and one that remained for quite long. An early emerging concept with conical springs can be seen in Figure 32. The concepts containing conical springs served two main purposes, firstly to mimic a potential non-linear relationship of force and compression depth during chest compressions. Secondly, an additional benefit with using conical springs compared to traditional linear springs was that due to their geometry during compression, they take up significantly smaller space when compressed, thus clearing vertical space in the stiffness module. This was a benefit since the vertical space was a constraint in early prototyping stages.

The reason to discontinue the conical spring concept was mainly based on concerns regarding the repeatability in measurements in the LISA III if the stiffness module is based on conical springs. With a conical spring system, there would be higher demands on ensuring the exact same zero-position for the measurements since a slight difference in the start position will yield bigger differences at max depth due to the steeper force-depth curves here.

The vertical space constraint was solved by an idea to instead place the spring modules on the sides of the impact plate and instead lowering this. Thus gaining plenty of vertical space and no longer relying on the compact conical springs.

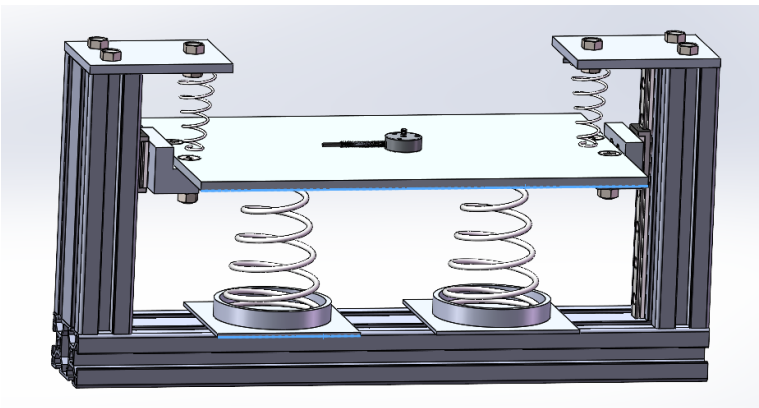


Figure 32: An intermediate solution of the LISA III stiffness module with the conical spring concept.

5.2.2 The Lowered Impact Plate Concept

A big milestone towards reaching the final solution was when the lowered impact plate concept emerged. The first steps toward this solution was placing the decompression springs on the sides and thus lowering the total vertical height. Later all springs were placed on the sides. Two early versions of this concept are presented in Figure 33 below.

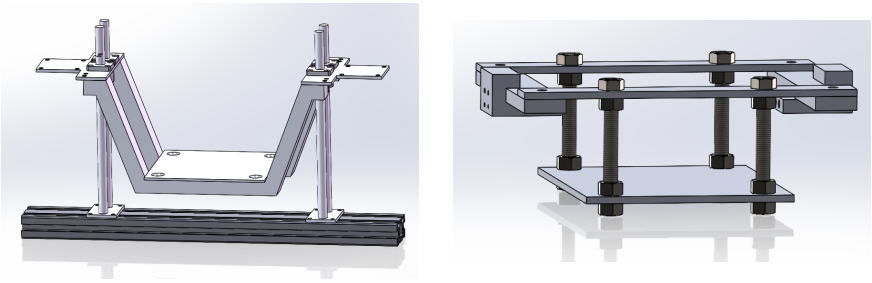


Figure 33: Two early solutions for the lowered impact plate.

Several iterations of this concept were evaluated against each other and finally one was chosen that was believed to be the most stiff and compact, while still remaining as light as possible since this part will be in motion with every compression.

5.2.3 The Guided Spring Concept

The guided spring concept was one of the final promising concepts for the LISA III stiffness module. This concept was the first one providing guides for the springs, thus making the construction more robust and secure. The positioning of the springs directly on top of each other was a first step towards a more compact solution, see Figure 34. This was also one of the first concepts with a lowered impact plate, saving vertical space and thus allowing for testing even on the smallest chest size.

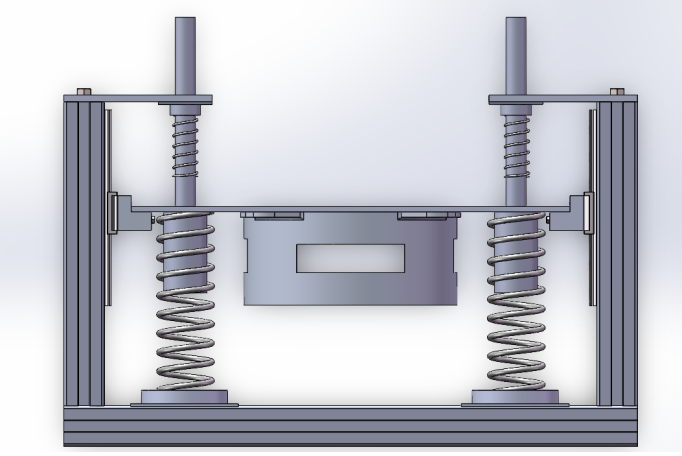


Figure 34: An intermediate solution of the LISA III stiffness module with the 4-spring stiffness module concept.

The two main reasons that this concept did not progress was firstly that it demands four separate force sensors to accurately measure the force without placing the sensors on the moving impact plate. The second main reason this concept was discarded was due to the opposite facing linear guides. These types of guides are not originally meant to be installed facing each other like this. Especially since this concept relies on this vertical motion being smooth and reliable over long time and many cycles. Additionally, these linear guides are one of the more expensive options, and it was therefore concluded that they were not a good fit for this implementation.

5.2.4 The Bushings Concept

Another concept was using bushings instead of linear guides to align the vertical motion during compression. Bushings are a mechanical component providing a controlled interface between two components, by damping the movement with the use of rolling elements. The bushing used in the project is presented in Figure 35 below.

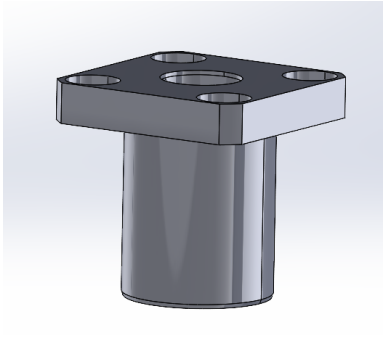


Figure 35: The type of bushing used for the concept.

These bushings were a better choice than linear guides mainly due to price and the bushings being more suitable for using several in the same construction. To make the stiffness module structure as compact as possible, and at the same time remain the robustness, different placements of the bushings were explored, see Figure 36.

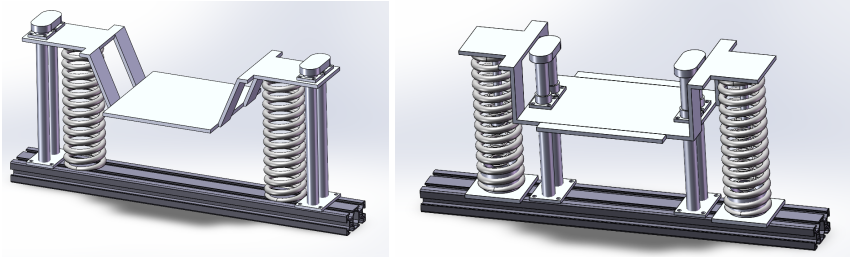


Figure 36: Different placement of the bushings and different angles to the impact plate were tested to find the best rigid and space-efficient structure for the stiffness module.

5.3 Intermediate Testing

5.3.1 Simulating Structural Deformations

Additional to testing of the full final prototype, some testing and simulation of intermediate prototypes were conducted to quickly eliminate or verify function of the intended solution. As an example, a deflection simulation was conducted to quickly evaluate the plausibility of using a 8 mm steel rod instead of aluminum profiles for the stiffness module base. A model of the set up was created and loaded at the center with 1200 N, as this is the highest force exerted to the equipment, given by the specifications. The results are presented in Figure 37.

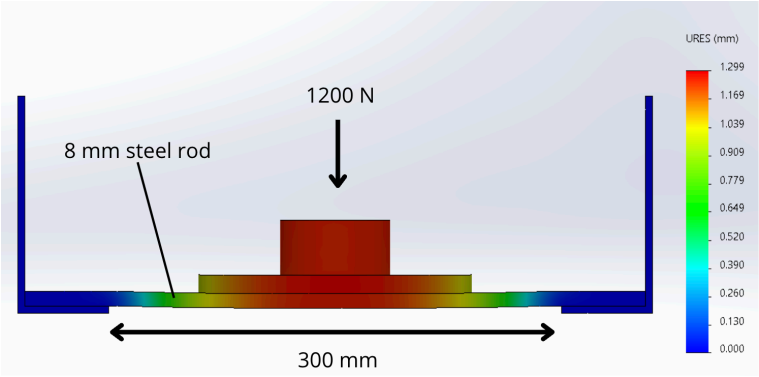


Figure 37: Evaluation of deflection for thin steel rod as base.

The results of this evaluation revealed deflections up towards 1.299 mm at the center (red in Figure 37), given the 1200 N force, which was exerted at the center point. This deflection was considered to be too high for this application. Thus this concept could quickly be discarded and the conclusion was that a stiffer base was needed.

5.3.2 The User Interface

For the prototyping it was important to create a user interface with an engaging design. By evaluating with potential users, one can overcome barriers that can cause accidents or damage the test equipment [37]. For this specific isolated design stage, five users at Stryker/Jolife AB were introduced to LISA III. They were asked how they would want the design for locking mechanism and height adjustment to be with focus on tolerance for errors and safety. Afterwards the findings from each demo were summarized and concepts emerged as a result. The different concepts can be seen in Figure 38 and 39 below.

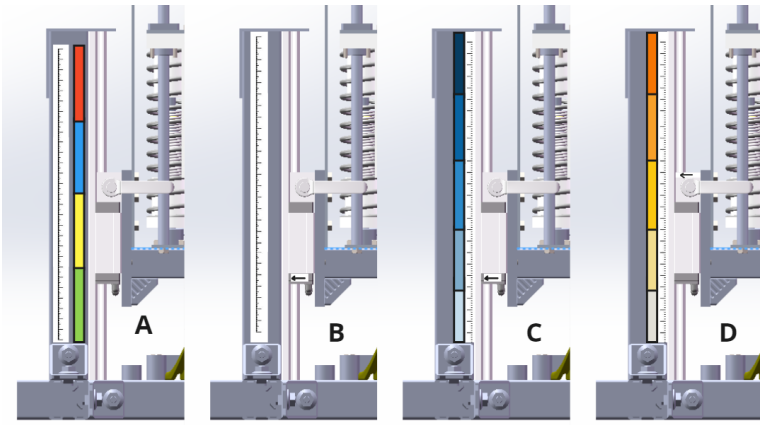


Figure 38: The height adjustment visualisation. A: colored height ranges and precise measurement. B: A precise measurement and pointing arrow to indicate position at the measuring tape. C: The arrow pointing closer to the measuring tape for precise measurement. D: Another placement for the height indicator and other colors following Stryker aesthetics.

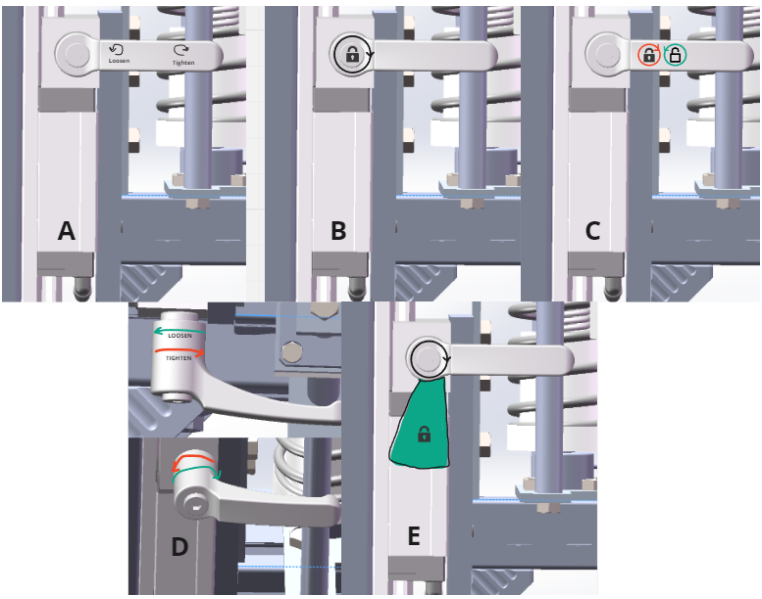


Figure 39: The locking indication. A: Tighten by turning clockwise and loosen counterclockwise. B: An indication for locking by turning it to the right. C: Same as for concept A but with colors and icons. D: another placement than in A. E: a zone indicating it is securely tighten.

Regarding the height adjustment, it was important for all users to have an interface with a clear distance measurement. It was also favourable to have some kind of colorful division between potential chest height zones, if the user only wanted to perform tests within a specific range. The final prototype will nclude a triangulation laser connected to a computer for precise measurement. The measurement on the sides are therefore more of a guidance for the user and the precise measurement can be done with the help from the computer. Regarding the placement of the arrow indicating the height, it was placed differently for some users. However it was important to place it as close to the distance measuring a possible to ensure more accurate reading. As for secure locking, it was important to easily see in which direction the locking would be. Concept B did account for this in an easy and straight forward way. Concept E specified in what position the handle would be in to be locked. For future enhancements it would therefore be some sort of combination between these two concepts. For this prototype version, no implementations were made. More tests and users included in future evaluations will result in a safe and efficient interface for this test equipment.

6 Final Solution - LISA III

In this section the results of the LISA III development process will be presented. Testing and simulation will be covered as well as an in depth presentation of the final concept, its subconcepts and finally the physical prototype.

6.1 Final Concept

The final concept in full, is presented in Figures 40, 41 and 42 below. The first contains the LUCAS device mounted on the test equipment whilst the last two figures include the LISA III on its own.

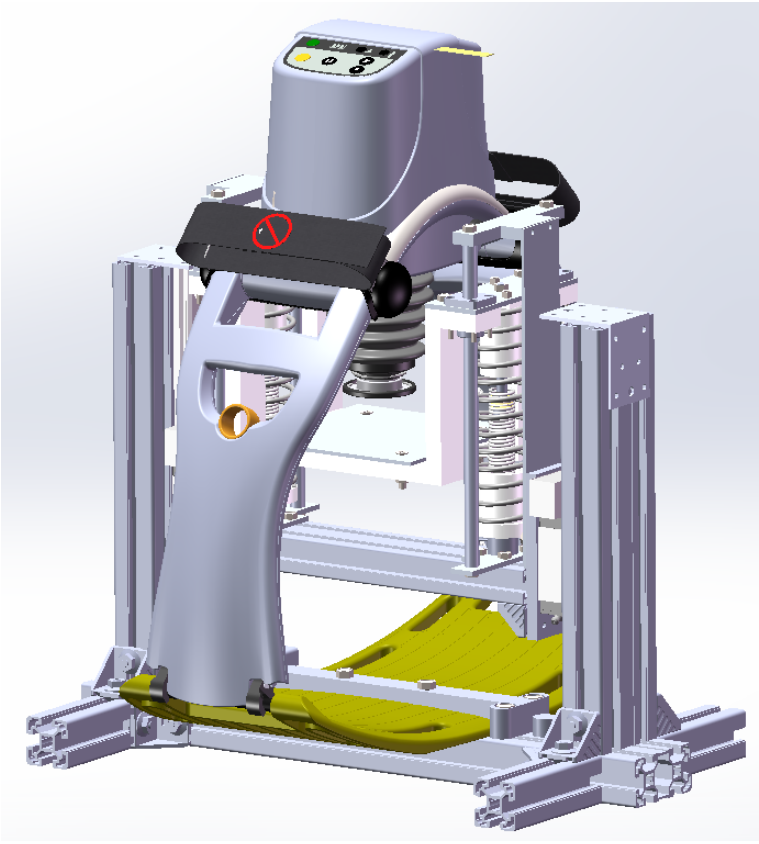


Figure 40: 3D model of the final concept of LISA III with LUCAS mounted.

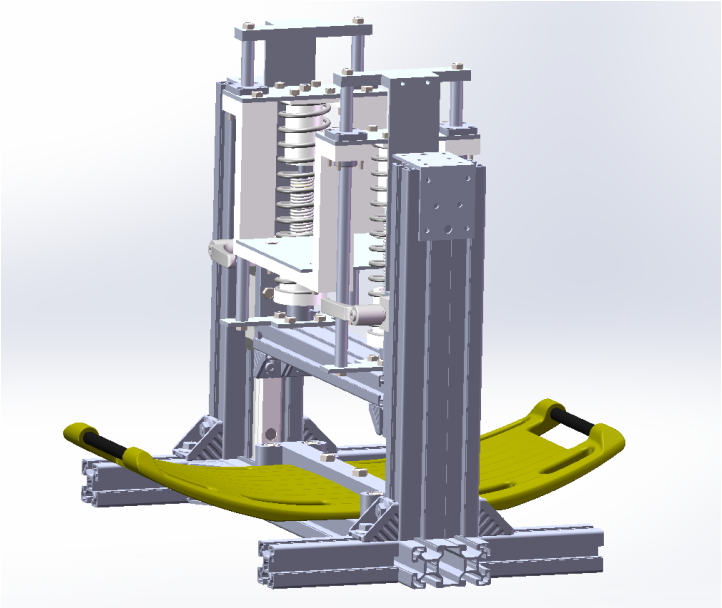


Figure 41: 3D model of the final concept of LISA III, side view.

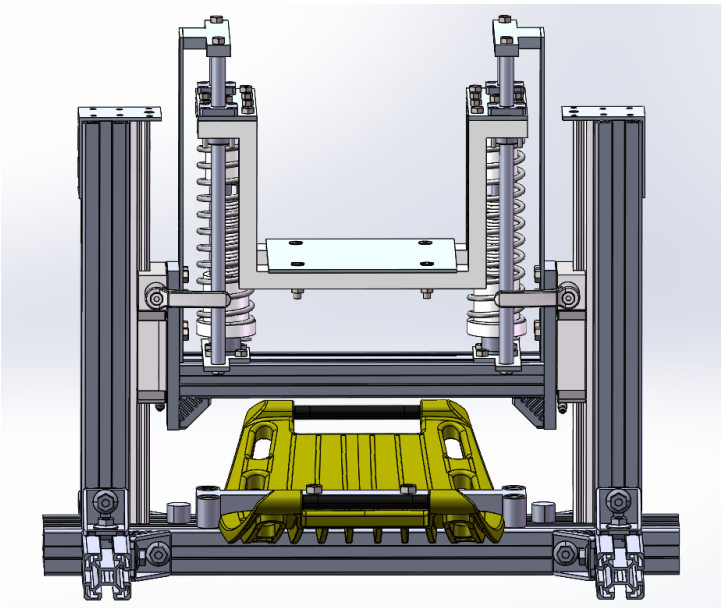


Figure 42: 3D model of the final concept of LISA III, front view.

Each subconcept (the main structure, height adjustment, stiffness module and back plate integration) will be presented and explained separately in detail below.

6.1.1 The Main Structure

The main structure is constructed with three 40x80 aluminum profiles and four 40x40 aluminum profiles from Bosch Rexroth [34]. These are connected with compatible 40x40 brackets, see Figure 43 and 44. It is a two pillar solution standing on a horizontal profile, with some extra space for fine adjustment on the horizontal base profile. By using aluminium profiles it is easy to change the structure without having to order new components, perfect for concept realization. This is due to the grooves in the profiles suitable for brackets allowing for a 90 degree connection. The dimensions fit the previously given specification of 1000x550x500 mm, and gives the prototype a robust frame to stand on.

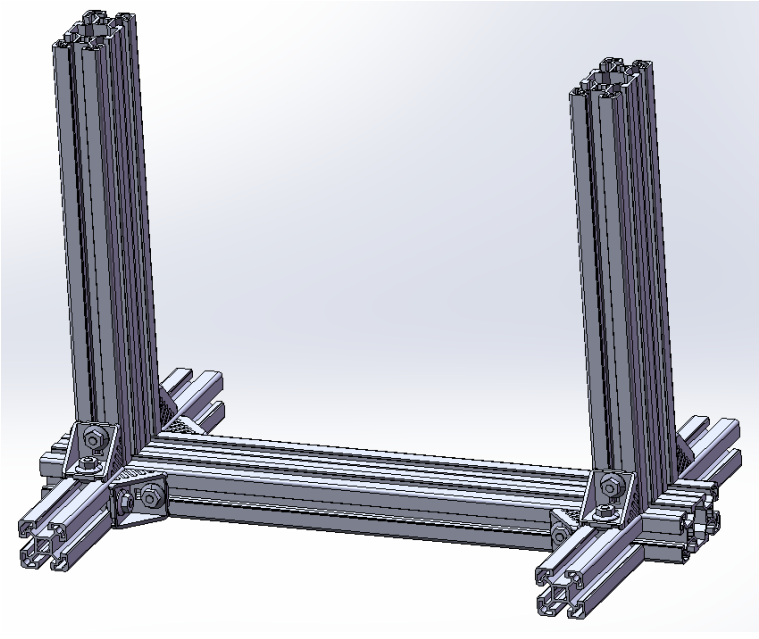


Figure 43: The main structure built up of aluminium profiles and connected through brackets.

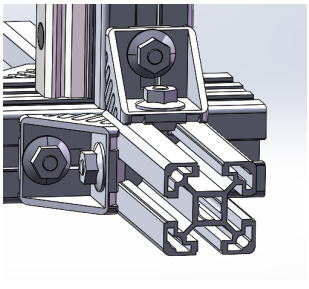


Figure 44: The brackets used to connect the main structure.

6.1.2 The Height Adjustment

The height adjustment is realized by two opposite facing linear guides, each located on the two aluminium profile pillars, connected to a manual clamping element. The linear guides are the MSB 25S and the clamping elements the HK 2501 A-PHK 25-1 manufactured by PMI Linear Motion Systems [38]. They were selected carefully based on holding force and moment resistance. Fixed end moments were calculated to obtain numbers on expected forces. This is explained in secition 2.8.3: Fixed End Moments. The holding force of the clamping elements are 1200 N each, yielding a total of 2400 N, which is well above the expected force of up to 1200 N, set by the specifications. The guides are interconnected via an aluminium profile with the dimensions the 30x60 mm. To stabilize and connect these two elements, a connecting plate was machined, see Figure 45.

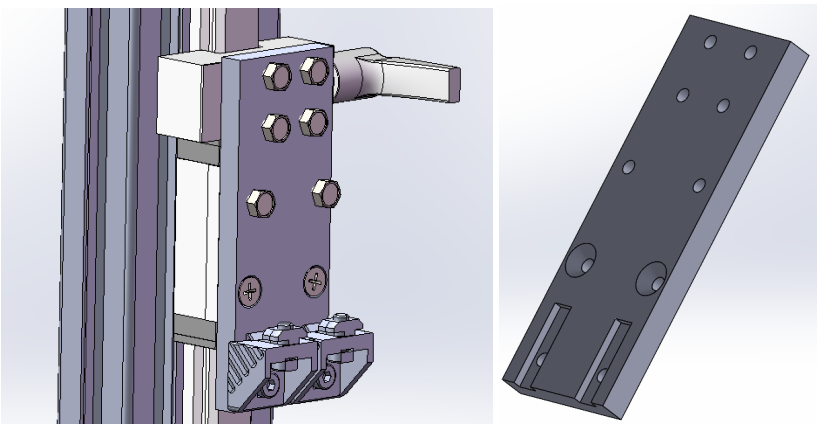


Figure 45: The assembled height adjustment system with linear guide, rail, clamping mechanism, brackets to support the horizontal profile and the connecting plate. The connecting plate was machined to act as a connecting element between the horizontal aluminum profile and the linear guides.

The range of chest heights that can be tested for on this model of LISA III are from 150-340 mm and not 140-340 mm as initially set. This was due to limitations in vertical space making it particularly challenging to allow for such low chest heights. In consultation with the engineers at Stryker/Jolife AB, it was decided that 150 mm was acceptable as a lower limit. This range allows for tests on all chest heights that the LUCAS can currently operate on, with some additional margin both under and over the current operating range of the LUCAS. Below the height adjustment system are two dampers, placed on the horizontal base aluminum profile. These are implemented to ensure minimal damage if the structure were to be dropped. At the top of the rail of the height adjustment is a stopping element, specifically placed there to ensure that the linear guides are not accidentally removed from the rails.

6.1.3 The Stiffness Module

The final concept for the stiffness module is presented in Figure 46 below. It is a U-shaped impact plate combined with two tension-compression spring modules going by the working name the Spring-in-Spring solution. The impact zone is built up of two 3D-printed coat hanger-like structures, later to be changed to aluminium, and a square aluminium plate acting as the impact plate. To ensure stability, two shafts on each side with bushings are connected to the impact plate, thus providing a fully vertical motion and robustness of the structure. On each side of the shafts are two long aluminum plates that serve two separate purposes. Firstly, to provide extra stability in the structure and secondly, to act as a protection to decrease the risk of injury. The force sensors are placed directly underneath the springs and can thus measure both compression and decompression forces exerted on the impact plate.

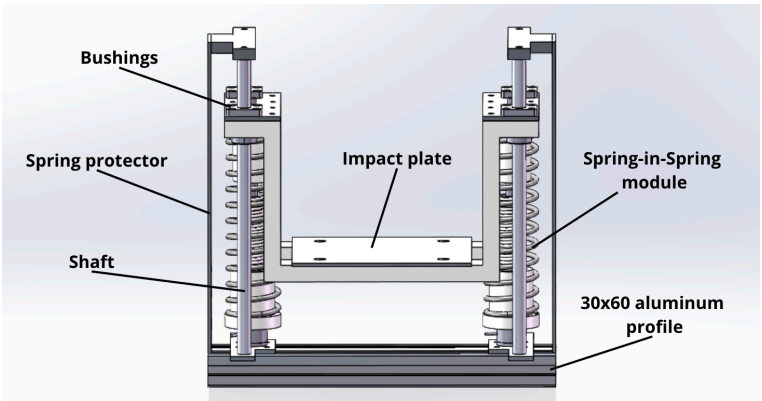


Figure 46: Final concept for the stiffness module.

A close-up of the mechanics of the concept is presented in Figure 47. The main idea of the Spring-in-Spring solution is to allow for realistic resistance both in compression and decompression. The outer spring is a compression spring, with a stiffness closely matching that of an average human chest during chest compression, based on the results from the biomechanical research and clinical data analysis that were conducted for the project. The inner spring is a tension spring, responsible for the resistance during the decompression of the chest.

During compression, the tension rod as depicted in Figure 47 is free to move within the tension spring, thus only the compression spring is active at this stage. During decompression, when the suction cup is pulling the chest up, the tension spring becomes active instead by being pulled out by the rod. Since the compression spring is only attached on the bottom end, it is not active during the movement upwards from the zero position. Figure 48, illustrates the function of the concept.

For the rough prototype, springs from Lesjöfors standard range assortment are used, to test the concept. However, in the next generation of LISA III, specially ordered springs are needed. The reason for using customized springs is to more closely match the stiffness of the chest that is wanted and also to be able to withstand a larger number of load cycles. The intended springs and the ones used for this prototype are all presented in Table 4 below.

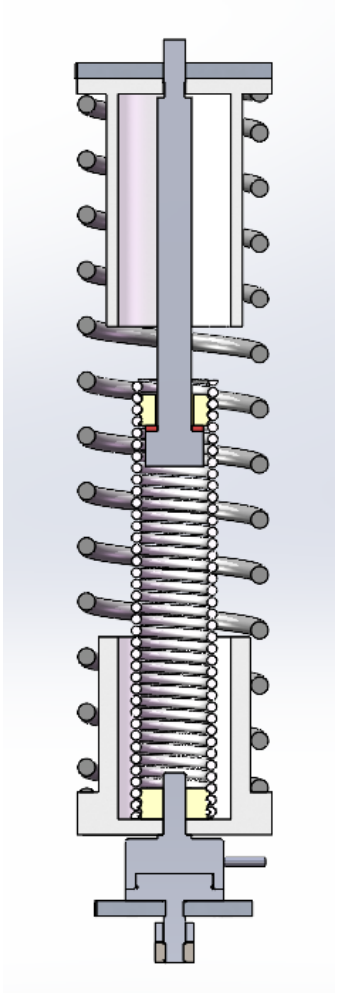


Figure 47: Section view of the Spring-in-Spring concept.

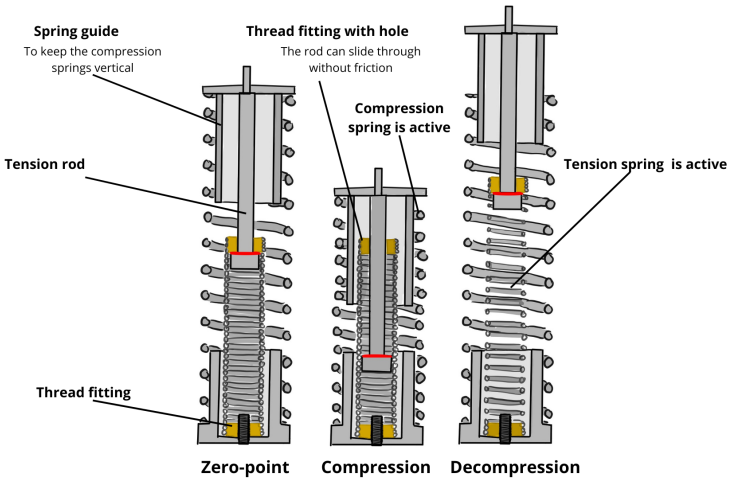


Figure 48: Functional illustration of the Spring-in-Spring concept.

Table 4: Dimensions of prototype springs and customized springs for next generation.

Springs	Type of spring	Spring rate (N/mm)	Free length (mm)	Outer diameter (mm)	Wire diameter (mm)
Inner spring	Tension	1.35	113mm	17	2.5
Inner spring (prototype)	Tension	1.35	113 (cut from 300)	17	2.5
Outer spring	Compression	4.4	180	39	4.5
Outer spring (prototype)	Compression	3.9	200	40	4.5

When choosing the spring rates for each spring, the addition of the weight of the system and the impact of gravity is taken into consideration. Therefore, the spring rate for the compression spring is slightly higher than what is sought after and the tension spring has a slightly lower spring rate.

The force sensors are directly attached to the spring module and can thus measure both compression and decompression forces. The chosen force sensors are two KM26z membrane-type force sensors by ME-Meßsysteme GmbH with the force range 1 kN, shown at the left part of Figure 49. [39] The benefits of these sensors are the small size and shape, with the main body only measuring 16 mm. The two M6 threads for attachment aligns perfectly with the structure it is to be attached to. For the rough prototype, a replica of the sensors were manufactured, see right image in Figure 49. The reason for this was that there had to be a proof of concept before, since the costs of the sensors were high.

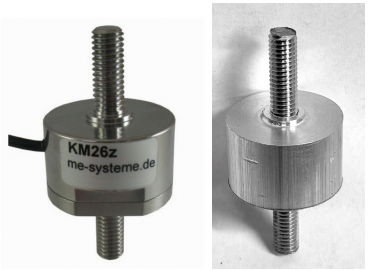


Figure 49: KM26z membrane-type force sensor in side-by-side comparison with the machined replica.

6.1.4 The Back Plate Attachment

The final solution of the back plate attachment is a spine-sized (25 mm wide) clamping structure that will fix the back plate, see Figure 50. For this prototype, this part is 3D-printed in plastic material Z-ULTRAT. However, to make this part more resilient, it would in the future be constructed in a stronger material, for example aluminum. To provide proper fixation, the contact surface of this part to the back plate is shaped as the negative of the back plate, using a cavity tool in Solidworks. This way, it has contact points all over the concave top surface of the back plate and secures it.

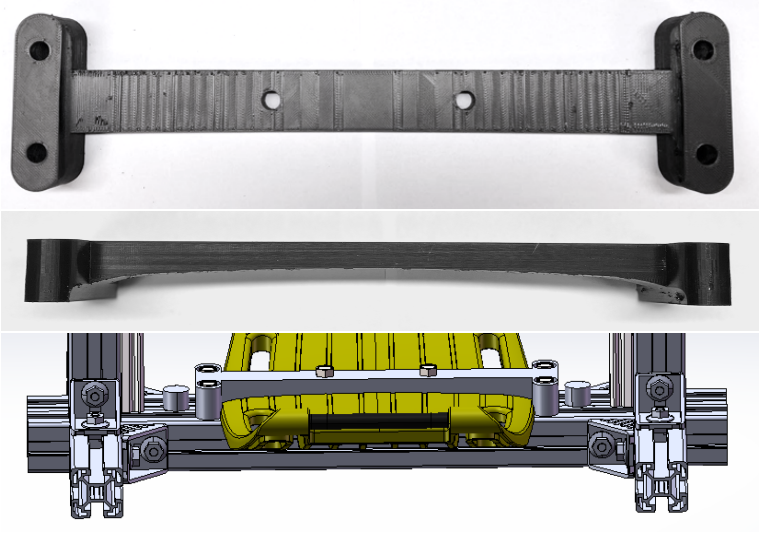


Figure 50: The final solution for the back plate attachment.

6.2 Final Physical Prototype

The final physical prototype is a rough first prototype, aiming to provide a proof of concept. The prototype weighs 15 kg thus ending up within the predetermined range of 20 kg. As for the dimensions, it measures 480x390x330 mm which is also within the set specification of 1000x550x500 mm. The main deviations from the intended final design of the LISA III are that prototype versions of the springs are used and that several components are 3D-printed. Below are photographs of the final physical prototype, both without and with the LUCAS device attached, see Figure 51-54.

Figure 51: The final physical prototype of the test equipment, going by the name LISA III.

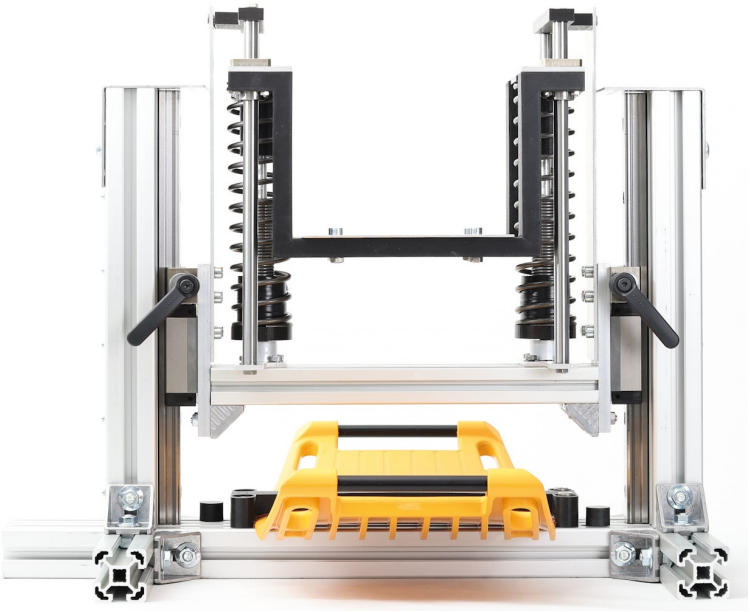


Figure 52: The developed LISA III test equipment with the LUCAS back plate mounted in front view. The compact and robust structure enclose the LUCAS device.

The 3D-printed components that will be replaced for future implementations are the back plate connector, which will be made out of aluminum to ensure robustness. The impact coat hangers, both top and bottom spring guides together with the bushing shaft top guides, seen as black in Figure 52, will also be constructed in more force enduring materials.

The force sensors are in this prototype machined from aluminum rods to mimic the real prototypes, since these components are expensive and will be purchased when the final construction is fully finalized. This also means that we have not been able to verify that the sensors function as intended with the developed design.

Some alterations were made during the construction process, due to new insights. Damping rubber was added attached to the back plate attachment, to provide a more secure fit of the back plate. The two holes for screws on the back plate attachment were not used, there were no need to screw through the back plate as originally intended, so these were left unused.

Figure 53: LISA III with the full LUCAS device mounted. The test equipment is tightly fit around, and is in the same range of dimensions as the LUCAS device.

Figure 54: Side view of the LISA III test equipment with the full LUCAS device mounted. As can be seen in the figure, the equipment is within the dimensions for the LUCAS device, leading to desired minimal uptake of space.

6.3 Testing and Simulation of Final Prototype

The final design was both simulated in SolidWorks Simulation and also tested with the LUCAS on the physical prototype.

6.3.1 Static Simulation

A static simulation was set up in SolidWorks to evaluate how well the main components affected by the compression would endure the maximum force. A force of 1200 N was exerted on a simplified model of the stiffness module. The main concerns were whether there would be high strain in the 3D-printed coat hanger-like structures and if there would be large displacements in the impact plate. The results are presented in Figure 55 below.

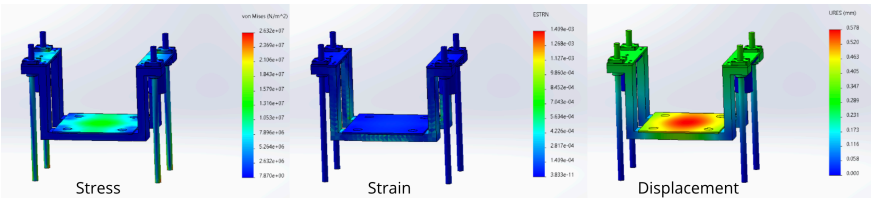


Figure 55: Results from the static analysis depicting stress, strain and displacement respectively.

When exerted to the 1200 N force, the maximum stress was around 26 MPa, equivalent strain 1.4×10^{-3} and displacement 0.58 mm. Sensitive areas were detected. Since the maximum force used here was chosen with extensive margin, it was decided to proceed with testing of the physical prototype. For the chosen materials of the components, these maximum values should be doable (hardened steel shafts, aluminum plate and Z-ULTRAT for the coat hanger-like structure).

6.3.2 Motion Analysis Simulation

A motion analysis study was performed in SolidWorks on a simplified model based on the final prototype design. The aim was to verify the motion in the system and the forces within. The simplified set-up is presented in Figure 56 below. It should be noted that all springs are set up according to the set parameters in SolidWorks, but only one is visible in the figure.

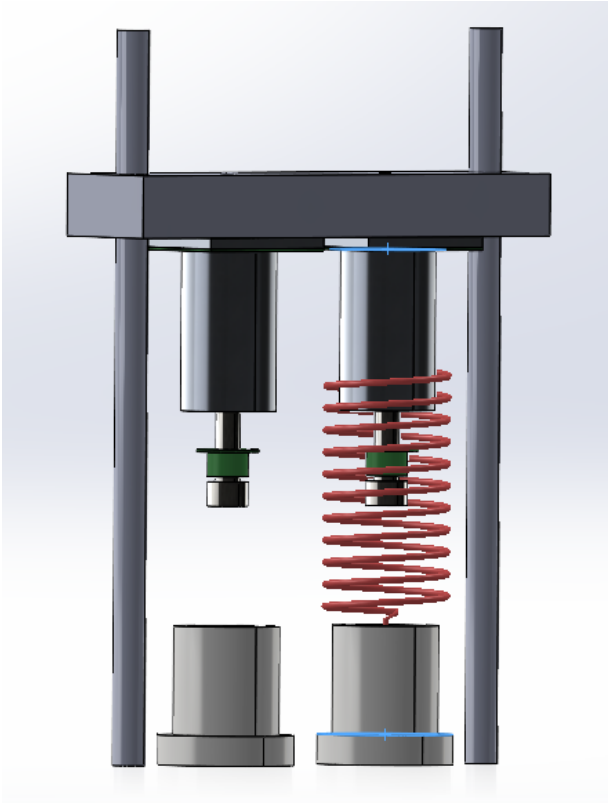


Figure 56: Simplified model for analysis of the final prototype.

The motion analysis was performed by using the motion pattern of the LUCAS device and by inputting the spring parameters. The results from this study did not lead to any new or surprising discoveries, however it confirmed that the model should function as it was designed to. The resulting curves for displacement over time and compression and decompression force over time are presented in Figure 57.

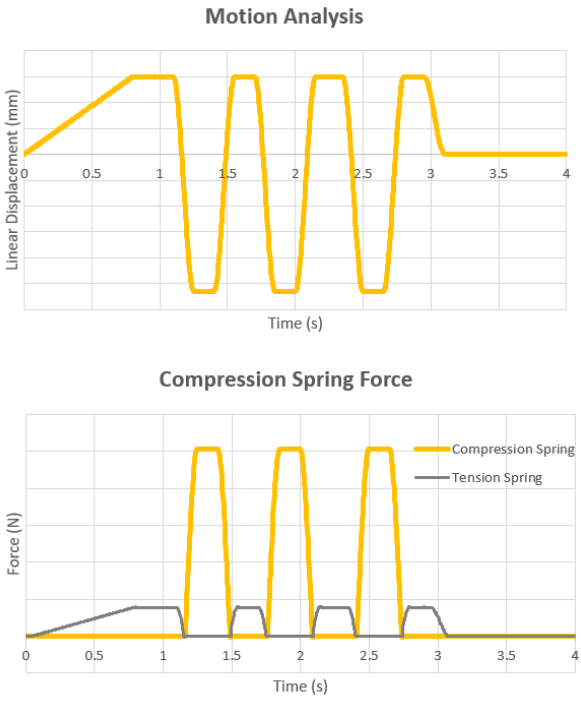


Figure 57: Results from the motion analysis. The upper figure presents the output in terms of displacement. The bottom figure presents the reaction force output.

6.3.3 Testing the Physical Prototype

The final prototype of LISA III was tested with the LUCAS device and successfully sustained compression with the LUCAS device. However, for use over longer periods of time, the current components will likely not be optimal, but since the goal was a proof of concept, it is considered a successful and promising concept. Data from the test runs were collected from the internal measuring system in the LUCAS. This could then be visualized with plots of the output and therefore verifying the force and depth exerted on the equipment. The compression spring performs as expected, but the tension spring appeared to be too stiff.

7 Discussion

The discussion will wrap up insights from the process, as well as discuss what could be improved and what to focus on during further development of the project. Finally, a conclusion of the project will be presented.

7.1 Implementing the Results from the Biomechanical Analysis

The project aim was to develop a test equipment for the LUCAS chest compression system. By performing a biomechanical analysis both consisting of a literature study and an analysis of clinical data, important insights and potential applications could be obtained for the new equipment itself. Direct implementations based on the results of the clinical data analysis were mainly the average chest stiffness values. The LISA III was designed to have a spring rate of approximately 8.4 N/mm aimed to replicate the stiffness that was found in this analysis. The average chest height values also indicates a neutral testing value for future use of the LISA III, even though it does not change the design of the test equipment since the height range of LISA III was based on the operating range of the LUCAS device. Even though the patient data included a total of 197 patients, the main predicament was that it only covered patients from small geographic areas. This consequently resulted in ranges not being representative for a larger population. It is however of importance to look at data from different geographic areas to form a realistic representation.

The literature study uncovered important findings regarding how the chest reacts to an applied force during CPR, where a non-linear relationship between compression force and depth was revealed. Several options for how to incorporate this finding in the test equipment were explored, for example by replacing traditional linear springs with non-linear conical springs. However, there were some crucial drawbacks of this option, mainly that they would add difficulty and decrease accuracy in the measurement. Due to the non-linearity of the conical springs, the zero-position becomes more crucial and small unintentional changes in compression depth could cause large differences in the measured force. The question emerged on what is most important between creating a fully realistic model or a more robust and accurate test equipment. While the equipment needs to be realistic enough for the conclusions from the testing to be applicable, it would be useless if the measurements are not accurate or reliable. For this project, the non-linear springs were put on hold due to this. For the future, it is likely that more realistic and human-like options for test equipment will be developed. It is however crucial to not compromise on the reliability and accuracy of the results.

7.2 Development of the Test Equipment

The concept development process included several iterations and there were multiple concepts that could have been suitable candidates. What influenced the concept outcome the most was the importance of using off-the-shelf components, in-house machining and reducing costs. Another limitation was the pre-specified

chest height range. To be able to have a range of 140-340 mm and fit the structure between the back plate and suction cup, the entire structure had to be very compact.

The testing of the final prototype resulted in some important insights and alterations to take into account for future development. Most significantly, the tension spring appeared to be too stiff and will need to be changed. The shafts with the guiding bushings had some problems in alignment. This was solved by widening the holes at their lower attachment point, to create some wiggle room. It is however important to take into account for the future.

The height adjustment worked well and even better than expected. There were some doubts regarding the alignment with two linear guides placed facing each other, since this is not what they are intended for. However, no issues regarding this arose during evaluation. The height adjustment is secured by two separate clamps, requiring the user to use both hands. Furthermore, the module that is being adjusted using the height adjustment system carries some weight. However, it is manageable for a single person to make the adjustments without problem. Additionally, since the height will not be adjusted too often, the most important was to make it a robust and sturdy adjustment system, which was achieved.

The stiffness module developed was a new, compact way to allow for resistance both in compression and decompression. Another main benefit with this concept was that the construction only relies on two force sensors (instead of four when using only compression springs). It was however complex to assemble, mainly due to difficulty gaining access to screws in the tightly designed model. Especially if this construction was to be produced at a larger scale, this would need to be reconsidered. However, the concept itself worked as intended, with the exception that the tension springs would need a lower spring rate to function perfectly.

The back plate attachment worked well, even with the prototype version that was 3D-printed. It successfully secured the back plate without restricting its natural flexion.

7.3 Future Work

The aim to make the stiffness module adjustable was not achieved in this first prototype. Other requirements that interfered with this were prioritized and it was therefore put on hold. For future work with LISA III, this should be a primary focus.

Another topic that could be further explored to achieve a more realistic test equipment involves investigating the optimal surface structure and material of the impact plate on which the suction cup is placed on. In reality, a metal plate is not a good representation of the chest since the suction cup will be attached more firmly on this than on an actual human chest. Various chest types present different challenges for the suction cup attachment. For instance, achieving a secure attachment would be more challenging on a hairy and uneven chest compared to a flatter, hairless chest. However, no chest will be as firmly attached to the cup as a flat metal plate. Exploring alternative materials, possibly with a permeable surface or a different topology could yield a less secure attachment, and thus a more realistic model.

It would also be interesting to focus on the user experience more in-depth. For example by including potential users in the steps of developing the interchangeable

chest stiffness, the appearance of height adjustment and the tolerance for error. The future goal would be to create a user-friendly test equipment, easy to connect with the LUCAS device and computer systems.

7.4 Data Collection, Ethics and Environmental Work

This project did not include any animal nor patient testing. No new data was collected for our analysis, but data sets from two earlier studies conducted by other researchers were used. The two data sets analyzed, the Beesems and Oslo data set, were both approved according to ethical guidelines. For the Beesems study, all the data were collected in accordance to the Utstein recommendations, which are guidelines established for uniform reporting of cardiac arrest. The Medical Ethics Review Board situated at the Academic Center in Amsterdam did also approve the Beesems study. They also gave a waiver for the requirement of informed consent.[29] For ethical reasons, the data sets were anonymized and it was not possible to identify the patients.

As for the environmental work related to this project, it was early on decided to use as much of the material already available to us in the workshop. By working with scraps, thus minimizing waste material. Furthermore the selection of distributors for the material was mostly based on the principle of short shipping distances, to minimize the emissions related to the transportation. The choice of aluminum profiles as a main structure was also influenced by the ease of rebuilding and reusing the parts for other projects or future versions of the test equipment. The 3D-printer was also a good complement for realizing ideas without buying material, just to end up leaving the tested concept behind. The material Z-ULTRAT used in 3D-printers does also have lower emissions in comparison to the intended metals used for the final concept, in terms of manufacturing [40].

7.5 Conclusion

To conclude, this project explored biomechanics of the chest related to chest compressions, in order to develop a representative and adjustable test equipment for the LUCAS Chest Compression System. The literature study revealed insights that could be incorporated in a future enhancement of the test equipment. More specifically, there were indications of a non-linear relationship between compression force and depth, lower chest stiffness for women and that chest stiffness decreased with age. The results from the clinical analysis were average values for both chest stiffness and height that the test equipment was based on. Additionally, correlations with factors such as age and sex revealed indications suggesting a decline in chest height and stiffness with age, and women exhibited a slightly lower chest stiffness compared to men. However, due to the small sample size, a statistically significant result was only observed in the case of women having smaller chest heights than men.

A first prototype of the new test equipment for the LUCAS device was developed and built. It is a two pillar solution with a height adjustable stiffness module centering around an innovative tension-compression spring module. It was successfully tested with the LUCAS device and serves as a proof of concept. However, some modifications are necessary, most importantly exchanging the tension

springs to ones with lower spring rates. The equipment is a rough functioning prototype with some components being temporary prototype versions. The main improvements for future development are making the stiffness module adjustable and purchasing customized parts that can endure larger numbers of cycles.

8 References

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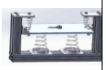
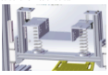
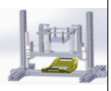
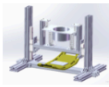
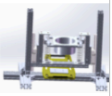
Appendix

Here follows the concept evaluation matrices performed on the height adjustment, the impact zone and the stiffness module.

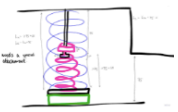
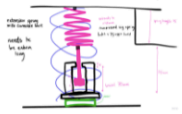
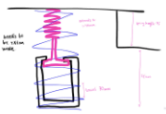
CEM:Height Adjustment

Criteria	Weighing (1-5)	Concept 1: Side single wheeler 	Concept 2: 3d-printer screw with guide with clamp 	Concept 3: 2 profile screw chain linked height adjustment 	Concept 4: Gas spring as lift support, clamps 	Concept 5: Connected gas spring height 
Total		172	211	173	169	138
Cost	4	3	3	3	2	1
Precision	4	4	4	4	3	3
Sufficiently load bearing	5	1	4	4	4	4
Tolerance for vibrations	5	2	4	3	4	3
Synchronization	4	5	4	4	4	2
Simplicity	3	3	5	2	4	1
Availability of components	4	3	5	2	3	1
Usability	4	4	3	4	3	5
Construction stability	5	1	4	3	4	3
Weight	3	4	3	2	3	3
Safety	3	4	4	3	2	2
Sufficient range of adjustment	5	5	5	5	2	2
Maintenance	2	4	4	3	3	2
Size	2	5	3	3	3	4

CEM: The Impact Zone:

Criteria	**Weighting (1-5)**	**Concept 1:** *Single horizontal plate* 	**Concept 2:** *Lowered platform with brackets* 	**Concept 3:** *Lowered platform with long screws* 	**Concept 4:** *Cylindrical cup* 	**Concept 5:** *Cylindrical cup with rails* 
Total		121	100	135	126	130
Cost	2	5	4	4	2	2
Size	4	5	3	4	3	3
Space maximization	5	1	3	4	3	3
Robust	5	4	2	3	4	4
Simplicity	3	4	3	4	2	2
Sufficiently load bearing	5	5	1	3	4	4
Weight	4	4	2	4	3	4
Safety	4	2	2	2	3	3
Sufficient range of adjustment	5	1	5	5	5	5
Total		121	100	135	126	130

CEM: Stiffness Module-SPRING-IN-SPRING

Criteria	**Weighting (1-5)**	**Concept 1: Internal slide** 	**Concept 2: External slide, extra long** 	**Concept 3: External slide, extra wide** 
Notes		Difficult to attach extension spring to circular slider. The slider will need to slide inside the extension spring (skinny).	Will demand more vertical space (additional length of the extension spring in compressed state (Ln))	Will be wider to make room for both extension spring and the stop block to both slide inside the compression spring.
Cost	2	3	3	3
Size	4	5	2	3
Sufficient range of adjustment	5	4	3	3
Construction stability	5	3	4	4
Change components	3	3	3	3
Precision	5	4	4	4
Synchronization	5	3	4	4
Weight	2	5	4	4
Total		115	106	110