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From strain to support

Designing an ergonomic tool to reduce work-related musculoskeletal disorder caused by ultrasound practice

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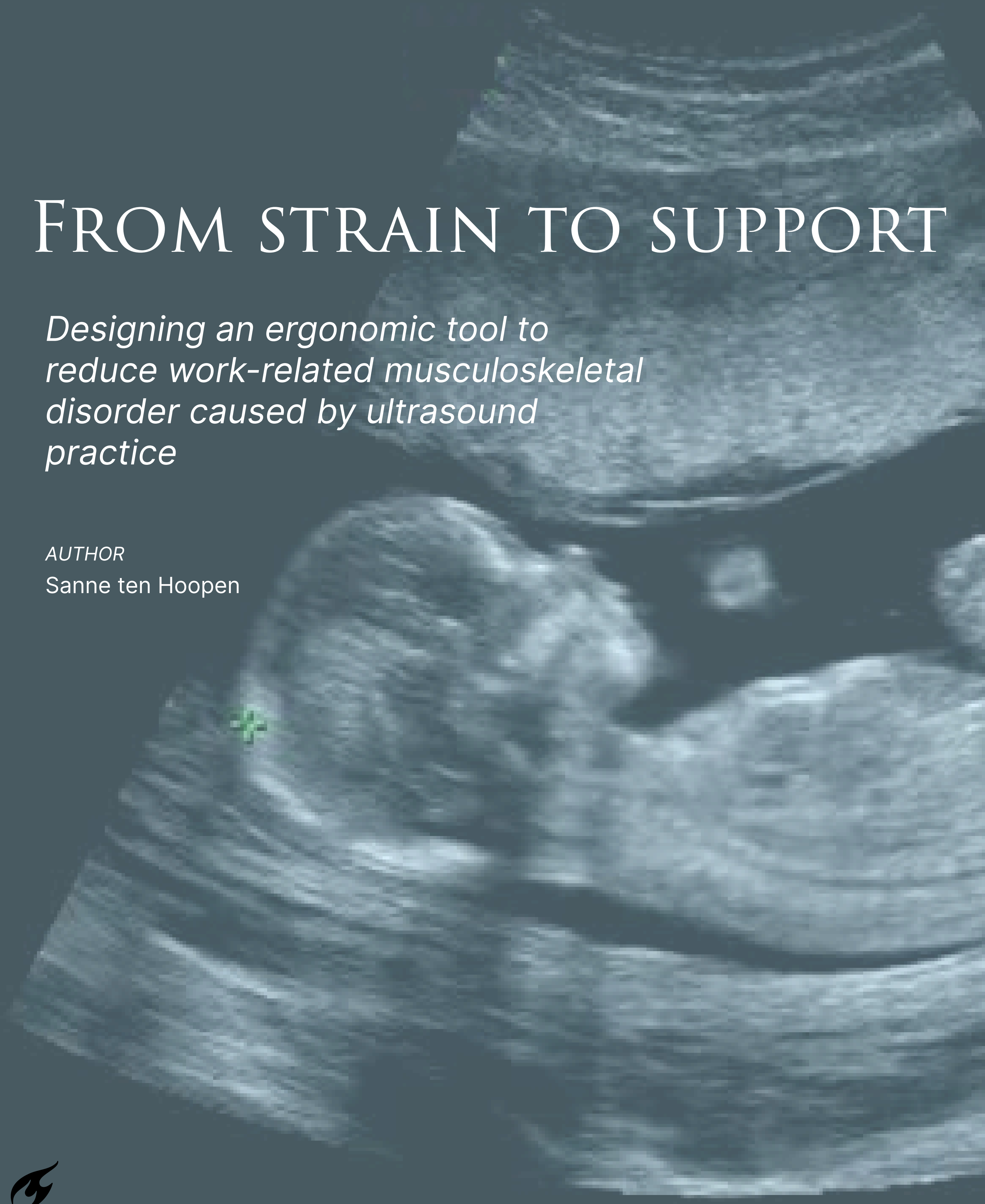

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Abstract

The aim of this graduation project was to develop an ergonomic support tool to prevent work-related musculoskeletal disorders (WRMDs) among sonographers, particularly shoulder strain during ultrasound procedures. The project began with an examination of the clinical context, ergonomic challenges and physical demands of sonographic work. Through observations, interviews and electromyography (EMG) testing, key factors were identified, including prolonged shoulder abduction and high muscle activity, particularly in the supraspinatus.

This research resulted in the development of Lofius, a supporting device designed to reduce shoulder load while allowing full range of motion. The tool was adapted for use in the departments of paediatrics and gynaecology, to accommodate the different procedures performed in each department. Prototypes were developed and tested with healthcare professionals, resulting in a design incorporating a hinge and sliding system to provide flexible, ergonomic support. Surface EMG testing showed that using Lofius correlates with reduced supraspinatus activity, which is important during long ultrasounds, demonstrating its potential to reduce fatigue and prevent injury.

This study concludes that Lofius is a promising starting point for addressing WRMDs in sonography. However, several limitations were acknowledged, including limited clinical testing and inconsistencies in the setup during EMG assessments. Future development should include extended clinical trials, design adjustments for improved support and infection prevention, and exploration of additional force-assistive solutions. Lofius meets the key design requirements identified through user-centred research, providing targeted support during sonography and addressing the most critical risk factor: sustained shoulder abduction.

List of Abbreviations

AIOS: *Arts In Opleiding tot Specialist* – A physician in training to become a medical specialist.

EMG: *Electromyography* – A diagnostic test that measures the electrical activity of muscles to detect neuromuscular abnormalities.

GUO: *Geavanceerd Ultrageluid Onderzoek* – Advanced Ultrasound Examination, performed to assess detailed fetal anatomy and detect potential abnormalities.

LLD: *Lateral Left Decubitus*

RdGG: *Reinier de Graaf Gasthuis* – Reinier de Graaf Hospital, a Dutch general hospital located in Delft.

SEO: *Structureel Echoscopisch Onderzoek* – Structural Ultrasound Examination, a routine detailed scan during pregnancy to assess fetal development.

TTE: *Trans-Thoracic Echocardiogram* – A non-invasive ultrasound of the heart performed by placing the transducer on the chest.

WRMDs: *Work-Related Musculoskeletal Disorders* – Injuries or disorders of the muscles, nerves, tendons, joints, cartilage, or spinal discs caused or worsened by work activities.

Terminology

Corpulent: Overweight or obese; having a large, bulky body.

Deltoid muscle: Thick, triangular muscle covering the shoulder joint, giving it its rounded shape.

Distal: Away from the centre of the body or point of attachment.

Gestational age: The length of a pregnancy, measured from the first day of the woman’s last menstrual period.

Humerus: The long bone in the upper arm, extending from the shoulder to the elbow.

Hypotensive syndrome: A condition involving abnormally low blood pressure, which may cause dizziness or fainting.

Inpatient ward: A hospital area where patients stay overnight or longer for treatment and care.

Lab technician (in Dutch: echo laborant): A medical professional trained to perform ultrasound procedures.

Lateral Left Decubitus: A body position where the patient lies on their left side, often used in imaging and cardiac exams.

Outpatient clinic: A medical facility where patients receive diagnosis or treatment without staying overnight.

Proximal: Close to or near the center of the body or the point of attachment.

Scapula: Also known as the shoulder blade; a flat, triangular bone at the back of the shoulder.

Sonograms: Also known as ultrasounds or "echos" in Dutch; imaging tests using sound waves to view organs or a fetus.

Subcostal view: An ultrasound view with the transducer placed under the sternum and angled upward.

Supine position: A body position where the patient lies flat on their back.

Suprasternal view: An ultrasound view where the transducer is placed at the base of the neck and angled downward.

Table of contents

1 Project Introduction

This chapter provides an overview of the project, setting the foundation for the development of a supportive tool aimed at reducing physical strain in sonography. It introduces the background of the problem, the design assignment, and the research questions that guide the process. The chapter also outlines the chosen approach, the clinical context in which sonography is used, and how ergonomics are currently addressed. Additionally, it highlights the involved stakeholders and defines the project's scope and deliverables.

1.1 Background

Sonography in healthcare
Ultrasound imaging, also known as sonography, is a non-invasive technology. There are two types of medical ultrasound: diagnostic and therapeutic (National Institute of Biomedical Imaging and Bioengineering, 2022). This report focuses on diagnostic sonography, since the hospital only uses ultrasound for diagnostic purposes. Ultrasound is used to create sonograms, also known as 'ultrasounds' or 'echo’s' in Dutch, of the inside of the body. Examples of these can be seen in Figure 1.1a

Ultrasound imaging is used in many departments and is a popular diagnostic method. This is also the case at Reinier de Graaf Hospital (RdGG), which has a total of 60 sonography machines, according to the medical technician. This study focuses on the paediatric and gynaecology outpatient clinics, as both departments have experienced work-related musculoskeletal disorders due to performing ultrasounds. Although other departments were found to experience the same problem, they were excluded from the study due to time constraints.

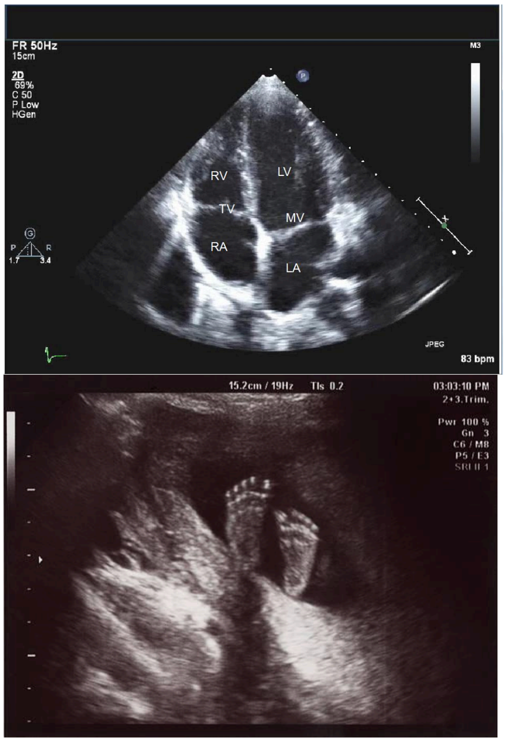


Figure 1.1a: Example of sonogram.
Top: heart (Moore, 2018), Bottom: baby feet (Sx, 2010)

Work-related musculoskeletal disorder in healthcare
Work-related musculoskeletal disorders (WRMDs) are a significant health concern, particularly in professions involving repetitive movements, awkward postures and sustained force. Sonography is one such profession (Fisher, 2015). These disorders are also prevalent at RdGG. Studies show that 75–94% of sonographers experience WRMDs, resulting in 20% absenteeism for extended periods or permanently (Zangiabadi et al., 2024). With hospital staff shortages set to quadruple in the Netherlands in the coming years, this could lead to increased work pressure and a higher risk of WRMDs if more colleges are unable to perform ultrasounds due to WRMDs (Wageman, 2024).

Health, safety and environment (HSE) coordinators at RdGG considered various solutions to prevent WRMDs and help sonographers who already suffer from them. They tried an arm support that fitted on a ergonomic stool and changes to the layout of the room but none were suitable for the sonography procedure.
The search by the RdGG is for a product with the capability to solve the problem of WRMDs.This question forms the starting point for this research project.

What product features are needed to prevent WRMDs at the Reinier de Graaf hospital?

1.2 Design Assignment and Research Questions

An assignment is formulated in collaboration with the healthcare professionals at RdGG. The design assignment led to different research questions.

Design Assignment
Design a functional prototype of a supportive instrument that reduces (physical) risk factors associated with sonography practices in both the paediatric cardiology and gynaecology department.

The prototype should be tailored to the specific physical challenges faced by sonographers in the chosen department and aim to greatly lower the incidence of WRMDs. It must be feasible to develop within 100 working days and align with the practical implementation needs of RdGG.

Research questions
A list of questions to guide the designer through this research process can be found below. These questions were answered using a variety of methods, including literature studies and tests. The section in which the answer to each question can be found is listed behind the question.

Research Questions	Section
1. What are the key risk factors contributing to WRMDs among sonographers in paediatric cardiology and gynaecology departments?	**2.3**
2. What are the key differences and similarities in procedures and ergonomic challenges faced by sonographers in the paediatric and gynaecology departments?	**2.3**
3. What design requirements must a supportive instrument meet to effectively reduce WRMD-related physical strain during sonography procedures in the paediatric and gynaecology departments?	**4.4**

1.3 Approach

A framework was chosen to give structure to this project. This project follows the Framework for Innovation, including the Double Diamond structure shown in Figure 1.3a. The diamond shapes allow for exploration interspersed with conversion to streamline the process. The Framework consist of the following phases: Discover, Define, Develop and Deliver (Design Council, n.d.). It is important to notices that this is not a linear process but circular which is represented with arrows. Each phases has his own methods included.

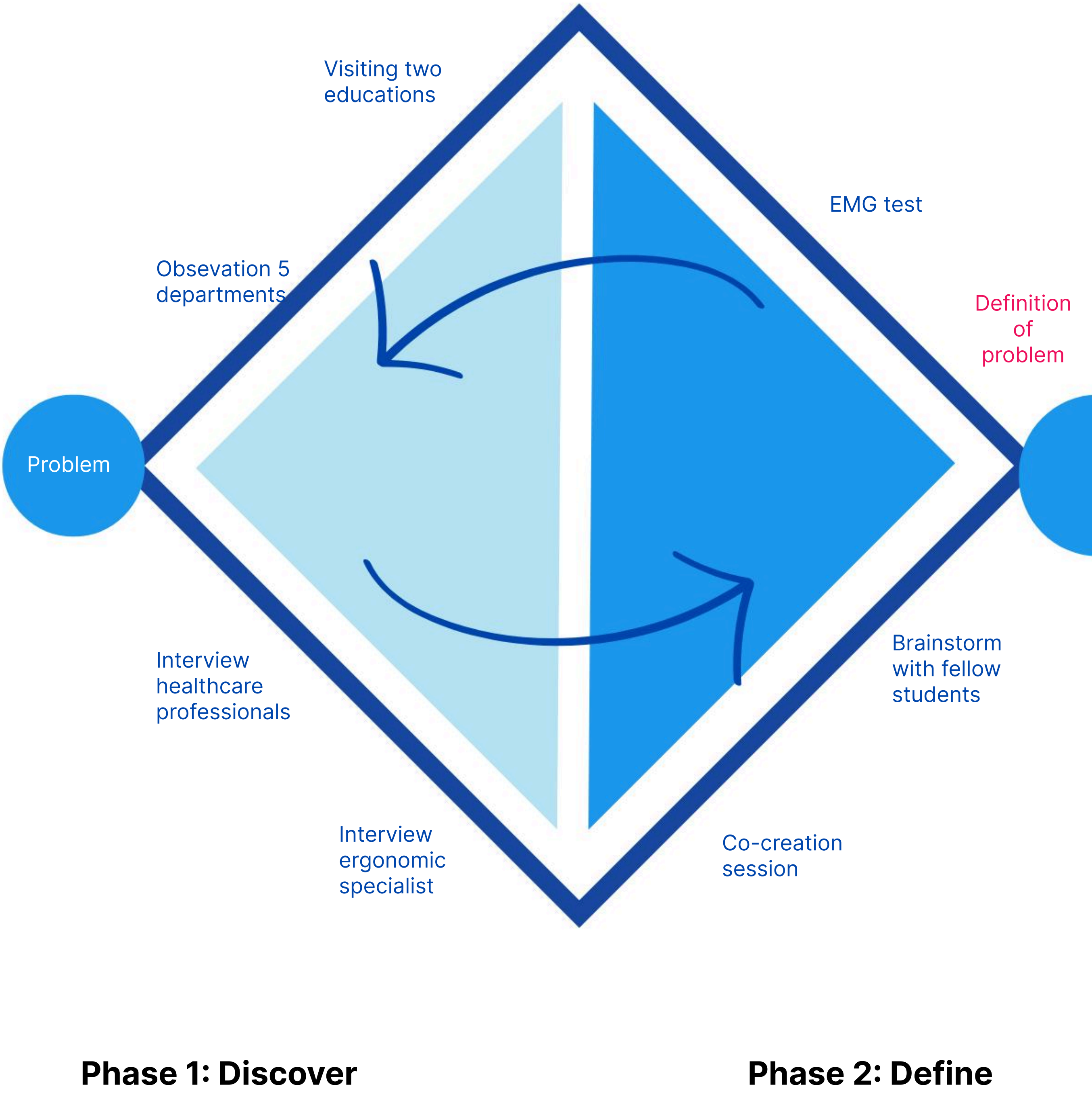
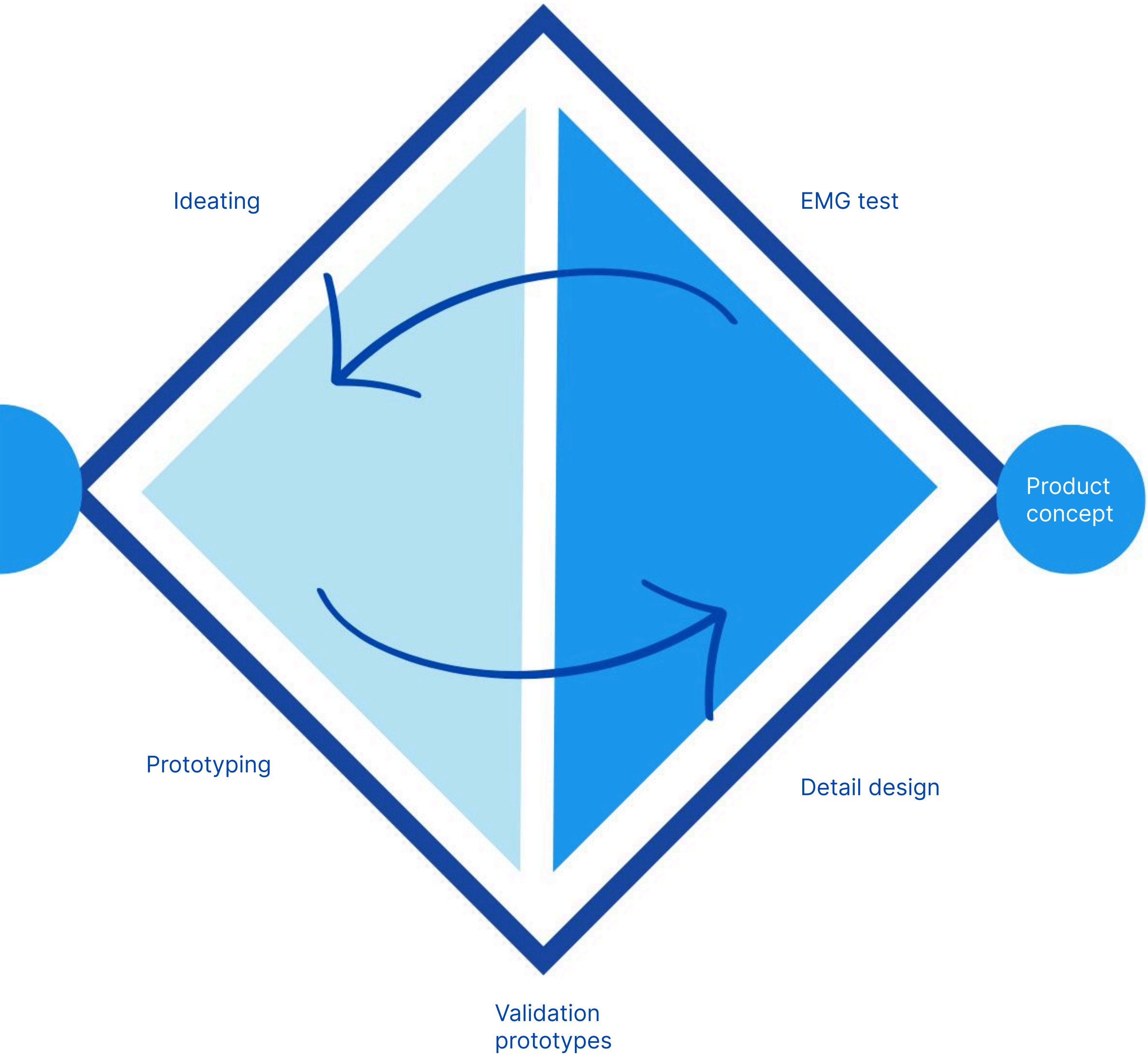


Figure 1.3a: Double Diamond

Design Insights

Throughout the whole report insights that are relevant for the final design will be stated using this format, marked by the box shown on the left.



Phase 3: Develop

Phase 4: Deliver

1.4 Clinical Use of Sonography

In order to understand what is required for this project, it is important to have an understanding of ultrasound equipment and its applications. Sonography is an essential diagnosing tool in the hospital. At the paediatric and gynaecology outpatient clinic, ultrasound is used for different purposes but with the same setup of equipment. Figure 1.4a shows the different parts of the equipment used to perform an ultrasound. In general, the computer is controlled with the left hand while the transducer is held in the right hand.

Paediatric outpatient clinic
The paediatric outpatient clinic provides care for all children between the ages of 0 and 18. Paediatricians work as part of a team of specialists. For example, for allergies, eating disorders, infectious diseases or cancer. This project will focus on paediatricians specialized in Cardiology. Children are seen with conditions such as heart murmurs, palpitations or chest pain.

As discussed with an expert paediatric cardiologist from RdGG, the reasons for an ultrasound are

- Abnormalities seen on the ultrasound by the gynaecologist before birth
- Family history of cardiac abnormalities
- Heart murmur
- Low oxygen levels
- Not growing properly
- Complaints of the patient
  - Chest pain
  - Fainting
  - Fever for a long time
  - Fatigue and inability to exercise

The ultrasound can be requested by a GP, clinical geneticist, paediatrician or obstetrician in consultation with the specialist. A full check for a new patient takes approximately 15-20 minutes, while a routine check takes 5-10 minutes.

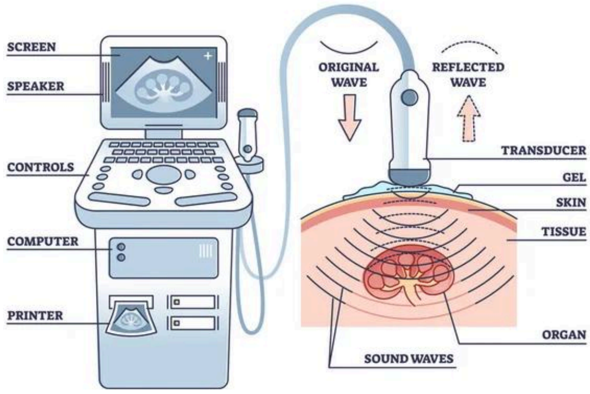


Figure 1.4a: Components and Workings of sonography (Vectormine, n.d.)

A heart murmur does not always have to have consequences, as 50% of children will have a heart murmur at some point in their lives. Only <1% of these murmurs are attributed to congenital heart defects ("aangeboren hartafwijkingen" in Dutch) (Huq & Rahman, 2024). It is therefore up to the paediatric cardiologist to decide whether an ultrasound is necessary. An overview of several congenital heart diseases can be found in Figure 1.4b.

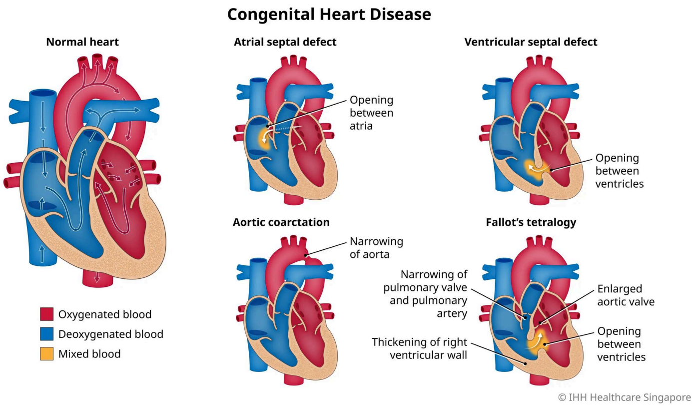


Figure 1.4b: Explanation congenital heart diseases (Gleneagles Hospital, n.d.)

Gynaecology outpatient clinic

The second department that will be looked at is the gynaecology outpatient clinic. This department helps patients with various complaints and disorders of the female genitals. Patients are treated for example on menstrual problems, endometriosis and unwanted urine leakage. The gynaecologists also assist women with complications during pregnancy.

The gynaecologists makes the ultrasound after consultation with the obstetrician. The gynaecologists looks at the child in the womb during pregnancy. This allows them to find out whether a child has certain conditions such as spina bifida (open back, see Figure 1.4c), omphalocele (open belly wall) or heart defects.
Every pregnant woman is offered an SEO (Structureel Echoscopisch Onderzoek in Dutch), the 20-week scan. The GUO (Geavanceerd Ultrageluid Onderzoek in Dutch) concerns pregnant women at increased risk of fetal structural abnormalities, women who have had a previous child with a structural abnormality, and pregnant women who need special ultrasound screening because they have had a previous child with heart and/or brain abnormalities or infections (BEN et al., 2023). It is possible that abnormalities may be found during an SEO or other medical tests, making a GUO necessary. GUO 1 is done with a high-risk pregnancy and GUO 2 is done if an abnormality is suspected at the SEO. GUO 1 takes 45 minutes, while GUO 2 takes 60 minutes. In the case of twins, it can take up to 90 minutes.

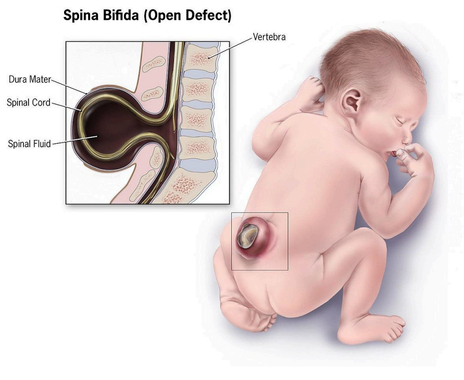


Figure 1.4c: Explanation of open defect. Open Back (Centers for Disease Control and Prevention, 2020).

Summary

Each department uses sonography for a different purpose, but with the same end goal of assisting in the diagnosis of patients. Other departments such as Cardiology, Vascular Centre and Radiology were also observed but not included in this project.

The table in Figure 1.4d gives an overview of the information from all the departments to make it easier to compare. As you can see, the duration of the sonography in the gynaecology department and Vascular Centre are the longest. Only in Cardiology and Radiology, left- and right-handed sonography are observed. The lab technologists perform sonography multiple days per week while the Doctors perform only two half days a week. Finally, they almost all use Philips, but the type of transducer is different.

It is important to define these similarities and differences to see if the product fits with multiple departments or only can be used in one specific department.

	Gynecology	Pediatric Cardiology	Cadiology	Vascular Centre	Radiology
Sonograph time	45 min/60 min/90 min twins	5-10 min, 15-20 min	10 min	20 min, 40 min, 50 min	10 min
Appointment time	45 min/60 min/90 min twins	30 min, 45 min	20 min	20 min, 40 min, 50 min	20 min
Right/left hand	Right	Right	Left/Right	Right	Left/Right
Who performs	Doctor	Doctor	Lab technician/AIOS	Lab technician	Lab technician
How many days a week?	2 half days a week	2/3 half days a week	3 half days - 6 days a week	4	4 half days
Number of patients each half day	4	4-5	5	6	10
Brand equipement	GE	Philips	Philips	Philips	Philips
Type transducer	C2-9, Curved Array (barely used)	S5-1, S8-3 (babies)	x5-1c	C5-1 (abdomen), L12-3 (legs, arms)	C5-1 (abodomen), L12-3(MSK), eL18-4(MSK, neck, scrotum)

Figure 1.4d: Overview logistic information

1.5 The Burden of Scanning: Work-related Musculoskeletal disorders

Definition
Clinical sonographers suffer from work-related musculoskeletal disorders (WRMDs). WRMDs are inflammatory and degenerative diseases of muscles, bones, nerves, tendons, and ligaments caused by occupational factors (Zangiabadi et al., 2024). These only include disorders that develop gradually and not disorders caused by trauma (CCOHS, 2024).

WRMDs in the clinic
During the examination, the ultrasound probe is pushed against the patient to capture images of tissues and organs. This creates reaction forces and torques on the shoulders and surrounding muscles, worsened by poor ergonomic positioning of the arm away from the body (see Figure 1.5a) (Murphey, 2017). The impact of WRMDs is significant, with research showing that one in five sonographers experience career-ending disorders (Sweeney et al., 2021).

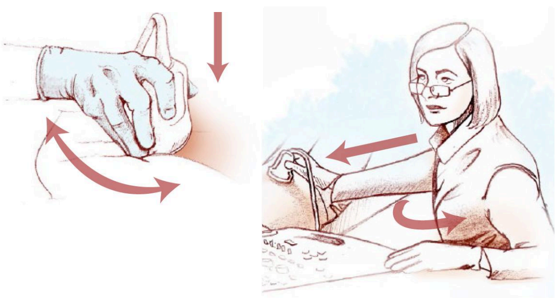


Figure 1.5a Movement of the probe and twisted position of the sonographer (Murphey, 2017)

Difference between department
WRMDs are common among sonographers, with research identifying the shoulder, neck, wrist, upper back, hands, and feet as the most affected areas. Several ergonomic risk factors contribute to WRMDs, including the force applied to the probe, prolonged arm abduction, and repetitive twisting of the neck and back (Fisher, 2015).

However, studies indicate that the prevalence and body regions affected vary between different sonography departments as shown in Figure 1.5b. A comparison between medical specialisations shows that cardiac sonographers report a higher incidence of musculoskeletal pain (86%) compared to obstetrics and gynaecology sonographers (65.6%) (Hogan, 2021). While musculoskeletal pain is a common problem across all sonography disciplines, sonographers from the gynaecology department report a higher percentage of wrist and hand pain compared to Cardiac sonographers (Hogan, 2021).

This difference is likely due to the unique ergonomic challenges of gynaecology sonography. The specialisation involves complex, time-consuming procedures that often require prolonged and repetitive movements. It was found that sonographers who perform more ultrasounds in a day for longer periods of time have the highest pain levels (Hogan, 2021).

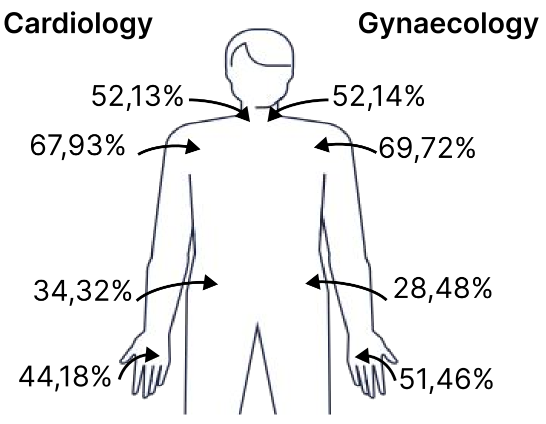


Figure 1.5b: Distribution of pain among sonographers who experience pain during sonography (Hogan, 2021)

Design Insights

Force, arm abduction and twisting of upper body are areas of interest for a product design.

How do WRMDs occur?

Often, WRMDs occur because the muscle, tendon or nerve that is injured.

When muscles contract, blood flow is reduced. Consequently, substances produced by the muscle are not removed quickly enough. The build-up of these substances causes pain. Next to this, the tendons in the hand have sheaths containing cells that produce fluid to lubricate the tendons. However, the tendons in the shoulder and elbow do not have these sheaths. They are therefore vulnerable, and repeated tensing can cause the fibres to tear, resulting in inflammation. Lastly, nerves are surrounded by muscles, tendons and ligaments that can swell, compressing the nerve (CCOHS, 2024).

WRMDs consist of many different disorders. To make these disorders more comprehensible, a list of the most common disorders in WRMDs is provided below. (NIOSH, 2006).

- Tendonitis: inflammation of the tendons
- Tendosynovitis: inflammation of the fluid-filled sheath that surrounds a tendon
- Bursitis: inflammation of the bursa. These are located next to the tendons near the joints. It acts as a cushion to reduce friction
- Muscle strain: differ from overstretching the muscle to tearing

These disorders can be seen depicted in Figure 1.5c.

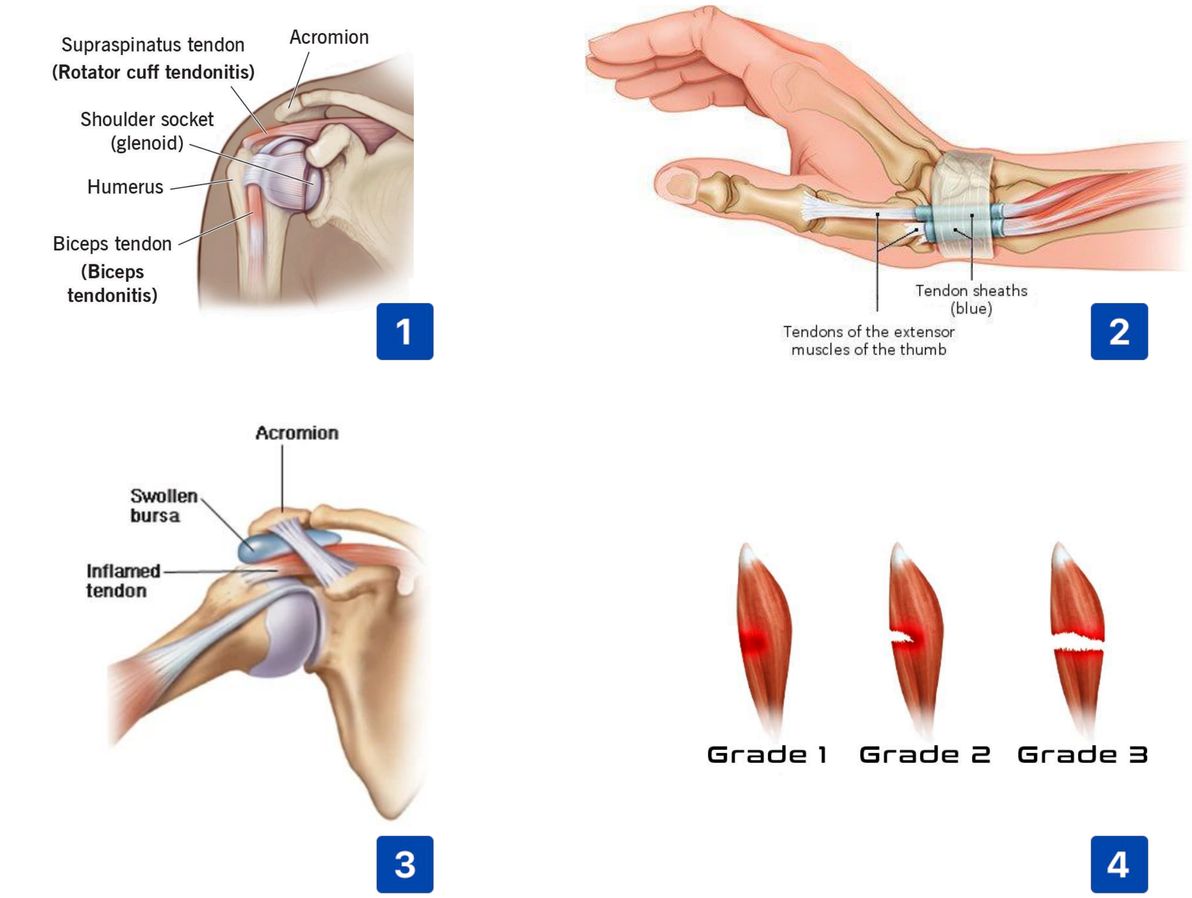


Figure 1.5c: 1:Tendonitis, 2: Tendonsynovitis, 3: Burstits, 4: Muscle strain

Awkward posture during sonography
Good posture is important during sonography, particularly given that research indicates sonographers spend around two-thirds of their working time performing ultrasounds (Zangiabadi et al., 2024). A common postural strain is twisting the torso towards the screen while maintaining arm contact with the patient. This often results in the scanning arm held in a contracted position with the shoulder elevated and abducted up to 90 degrees (see Figure 1.5d).

Such position deviates from the ergonomic guidelines recommending that shoulder abduction should remain below 30 degrees, while the forearm-to-arm angle should be close to 90 degrees to minimise musculoskeletal strain. Angles above 30 degrees accelerate the onset of fatigue in the muscle (Alshuwaer & Gilman, 2019).

The combined effects of arm abduction, shoulder elevation and neck rotation mean that sonographers often work in non-neutral, unsupported postures for extended periods (Fisher, 2015).

Next to this, research has shown that scanning is mostly static, especially when performing an ultrasound of the heart (Simonsen et al., 2017). Static posture reduces blood flow to the joints, which increases the load on the muscles and reduces the time to muscle fatigue (McDonald & Salisbury, 2019).

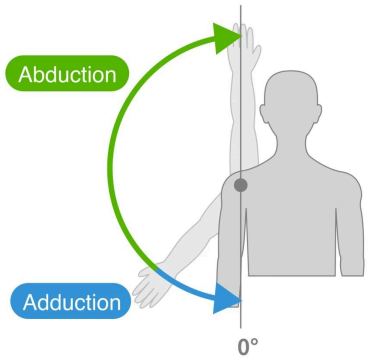


Figure 1.5d: Abduction

Type of grip
Sonographers use two main types of grip during procedures: the pinch grip and the power grip (shown in Figure 1.5e) Research suggests that using a pinch grip of more than 0.9 kg or a power grip of more than 5.5 kg increases the risk of developing WRMDs (Zangiabadi et al., 2024).

Although these forces may seem relatively low, studies show that sonographers, particularly those working in cardiac departments and scanning corpulent patients, often exert much higher grip forces. In some cases, the force required can be as high as 27.6 kg (Roberts et al., 2019). Also at the gynaecology department corpulent patient occur as shown in Figure 1.5f.

The force is a combination of gripping the probe, applying finger pressure to manipulate it into the optimal position, and applying downward force to improve image quality (Ulrich & Struijk, 2021). Despite these high demands in certain scenarios, the average grip force across procedures is approximately 3.96 kg (Zangiabadi et al., 2024). In addition, smaller transducers used in cardiology may limit the ability to use a power grip, potentially forcing sonographers to rely more on the pinch grip, which can contribute to increased stress on the fingers and wrists (Barros-Gomes et al., 2019).

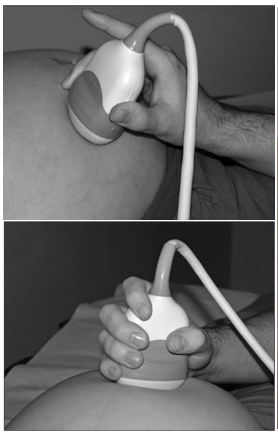


Figure 1.5e: Pinch vs force grip (Rousseau et al., 2013)


Figure 1.5f: Example force applied at the gynaecology department.

Wrist position
In addition to the type of grip, maintaining a neutral wrist position is critical to reducing strain and preventing WRMDs (Rousseau et al., 2013). A neutral position means keeping the wrist in line with the forearm, avoiding bending, flexion or extension. To minimize this stress, research suggests that sonographers should rotate the probe in the hand rather than twist the wrist to adjust angles (Harrison & Harris, 2015).

The influence of the scanning technique on WRMDs

In cardiac ultrasound, patients are typically positioned on their side also called lateral decubitus position (LLD), to allow for a clear view of the heart. Within this setup, three primary scanning techniques are commonly used (see Figure 1.5g). The pink lines illustrate the angles formed by the limbs in relation to each other. Each configuration has it own challenges and advantages.

Techniques 1 and 2 (T1/T2) are generally more effective in minimising strain on the upper arm, whereas Technique 3 (T3) enables the sonographer to rest their arm against the patient for additional support (Simonsen et al., 2017).

Research indicates that alternating between T1/T2 and T3 is the most beneficial approach, as it helps to distribute physical demands more evenly across various muscle groups (Simonsen et al., 2017). However, implementing this strategy can be challenging, as it involves switching between the dominant and non-dominant hand, something many sonographers are not trained to do.

Additionally, the risk of musculoskeletal injury varies depending on the use of their right or left hand. Studies show that right-handed sonographers are more prone to back, neck, and wrist pain, while left-handed sonographers are at greater risk of developing elbow and wrist injuries (Roberts et al., 2019).

At the gynaecology department, the alternation between hands would not effect the type of injury as the angles remain the same while at the cardiology the angles do changes as shown in Figure 1.5g.

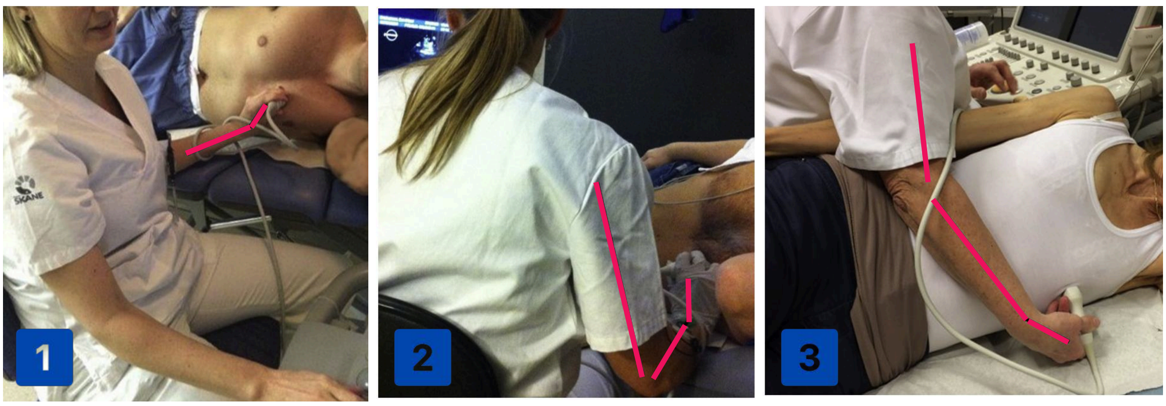


Figure 1.5g: The three scanning techniques in cardiology (Simonsen et al., 2017)

1.6 The Role of Education and Design in Promoting Ergonomics

Overlooked ergonomics during education
Ultrasound scans are performed by doctors and laboratory technicians. Doctors learn this skill while they are AIOS. This is when they are educated for a becoming a medical specialist. How they are taught ergonomics depends entirely on who is guiding them. During the observations, one sonographer mentioned that the first time he performed an ultrasound, he did not even know how to turn on the equipment. Ergonomics depends entirely on the teaching environment and the individual's own commitment and interest in the topic.

Several institutes in the Netherlands provide education to become a laboratory technician. Two large institutes were visited: Fontys in Eindhoven and Hogeschool InHolland in Haarlem.

At Fontys, the author attended a practical class on performing an obstetric ultrasound, which produces images of the embryo or foetus inside a woman's uterus, as well as her uterus and ovaries. Students are not taught any theory about ergonomics, but teachers do walk around and correct students' posture when necessary.

There is a small section in the information books of the students on this topic with the following tips:

- Make sure you are positioned directly in front of the machine.
- The probe is handled with the right hand and the machine with the left.
- You can lean on the patient for more stability, they won't mind.
- Do not lift your arm too high. If you need to lift your shoulder, the examination table is set too high or too low.
- For hygienic and ergonomic reasons, do not hang the probe cord around your neck.

At InHolland, H. Laurijsen (Physical and Mental Health Advisor at HMC) teaches a class in ergonomics during ultrasound practice. G. Plug, coordinator of vascular ultrasound, instructs his students to approach posture as if they were working behind a computer:
"The equipment is your screen; the probe is the computer mouse; and the patient is the mousepad. Your hand on the patient acts as a sensitive feedback system. Make sure that your limbs form 90-degree angles and that your elbows are next to your torso."

At both institutes, students learn to perform ultrasound exams with their right hand. This is a new skill that has to be taught, so it does not matter if you are left-handed is the reasoning. This is because the hospital setup is designed for right-handed people, and there is no time or space to change the setup at the institutes or in the hospital. The setups at the institutes can be seen in Figure 1.6a.

Figure 1.6a: Teaching setup: on top at Fontys, below at InHolland

Ergonomics addressed by Philips
At RdGG ultrasound equipment of the manufacturer Philips is used at all departments except for the gynaecology department who use equipment from GE.

To investigate the role of the manufacturer of the ultrasound equipment in ergonomics, three interviews have been conducted with different key players, including an implementation technician, a senior usability designer and an ergonomist from Philips.

The main finding was that Philips focuses on developing the equipment itself rather than adding supporting products to its portfolio. Philips conducts a lot of research on WRMDs due to sonography. Ergonomist and design director J. Mason mentioned that the question is not whether someone will experience WRMDs, but when. To prevent this, a radical change to the whole device is needed.

H. Ying, the senior usability designer, envisages a future where users are not constrained by equipment in determining their posture, but rather work with wireless transducers and AI to enjoy much greater freedom of movement. Using AI will also result in faster sonography, thereby limiting the time spent in non-ergonomic postures.

These conversations demonstrate that the manufacturer recognises the problem, but that the solution still requires a great deal of development and implementation time. Therefore, a support product that helps to prevent WRMDs will remain relevant in the years to follow.

1.7 Stakeholder Overview and Involvement

In this project, a lot of stakeholders are involved. Figure 1.7a shows the unite stakeholder matrix. In this matrix the importance of the stakeholder is plotted against the power. In this way, it is visual who needs to be kept informed and who is a key player in this project.

The four categories
The figure shows the mapping of the different stakeholders. The quadrants of the stakeholder matrix will be briefly clarified.

Close management of the product's users is essential. The product must work for them; otherwise, they will not use it. At RdGG these are the Doctors and Lab technicians.

The stakeholders who need to be kept satisfied are the board of the hospital and the HSE officers. The HSE officers will most likely recommend the product to users and obtain funding from the hospital board to purchase it.

The stakeholder who need to be kept informed will regularly come into contact with the product. For example, patients need to understand the product's purpose, and cleaning staff need to know what needs to be cleaned.

The stakeholder who need to be monitored don't have regular contact with the product. For example, physical therapists need to be aware of the product's existence so that they can recommend it if they notice WRMDs in their sonography patients. If the product prevents WRMDs, HR will need to hire fewer new sonographers. Additionally, technical staff need to know how to repair the product to ensure it has a long lifespan. Also, the infection prevention team needs to be consulted about infection risks. Finally, it would be preferable for the industry to be aware of the product, so that it can grow alongside the development of new ultrasound techniques.

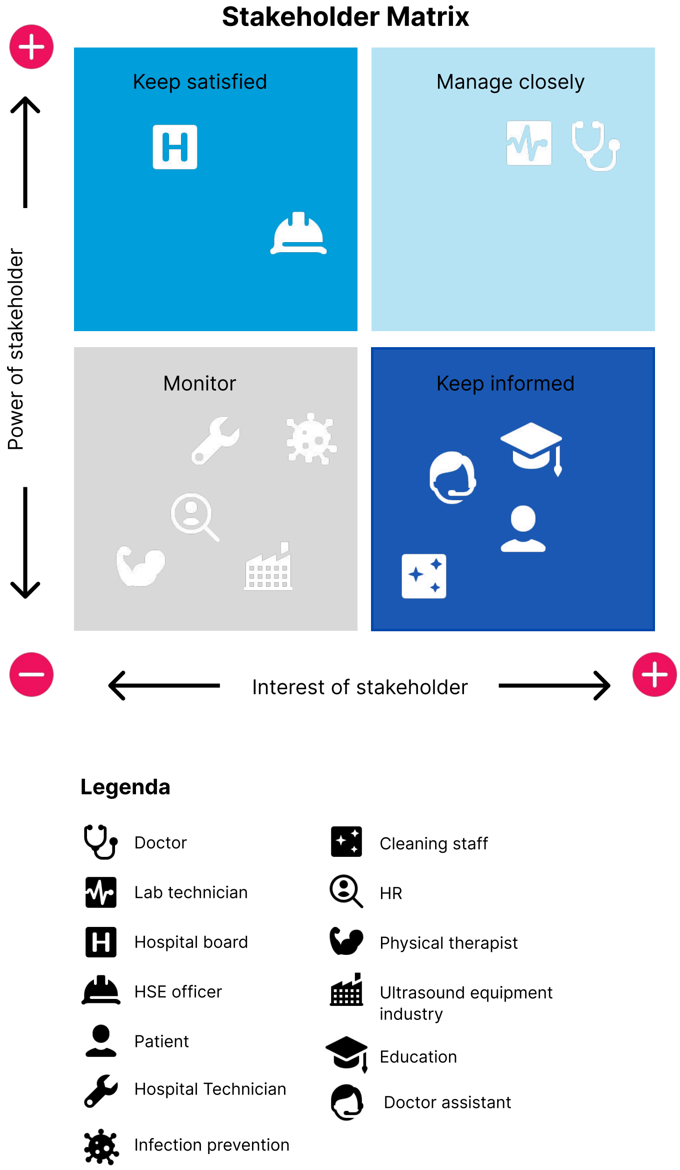


Figure 1.7a: Stakeholder Matrix

1.8 Scope: Combining Research Insights

The research discussed in this chapter led to a scope when combined. It is important to set a scope for the project to give direction to the design process.

The goal of this graduation project is to design a support product to prevent WRMDs due to ultrasound practice. The project scope is limited to the Dutch healthcare sector, with the RdGG as the primary research focus. Within the hospital, the focus will be on the Departments of Paediatrics (cardiology) and Gynaecology, but other departments will also be observed to gather more information.

The supportive product will not be a medical device, but an ergonomic tool. An expert on the MDR at the Faculty of Industrial Design Engineering has confirmed that if the product's purpose is to prevent WRMDs, it is not subject to the MDR. Therefore, only a CE marking is required. When produced in-house, this is also not necessary.

Together with the team from RdGG a list of project deliverables is made. These include:
- A prototype of the supportive product.
- A bill of materials of the supportive product.
- A start of looking costs.
- An overview of recommendations, limitations and future steps.

2 Explore Context

This chapter presents the findings uncovered during the exploration of the project context. It begins with an analysis of probe movement, followed by insights gained from observational studies conducted in the clinical environment. To further support and quantify these findings, an EMG test was carried out to assess shoulder abduction and muscle activity in various muscle groups. The chapter concludes with a summary of the key factors contributing to WRMDs in sonography.

2.1 Seeing with sound: Movement of the Probe

This section describes the basic knowledge needed to understand the movement of the probe that need to be made to perform an ultrasound.

Understanding what you see on the screen
To determine which side of the probe is left or right, one can tap the side of the acoustic lens (see Figure 2.1a). If movement is visible on the left side of the screen, then that is the left side of the probe. This is important for aligning the patient's orientation with what the sonographer sees on the screen, making it easier to interpret.

Figure 2.1b shows how the image is translated. If the probe is horizontal, as shown in the Figure, you are looking from the front. If the probe is rotated 90 degrees, you are looking from the left. The probe moves within this 90-degree field, allowing you to see cross-sections of the same structure, as depicted in Figure 2.1c.

Figure 2.1a: Acoustic lens

Figure 2.1b: Sonography probe used by technician on test equipment

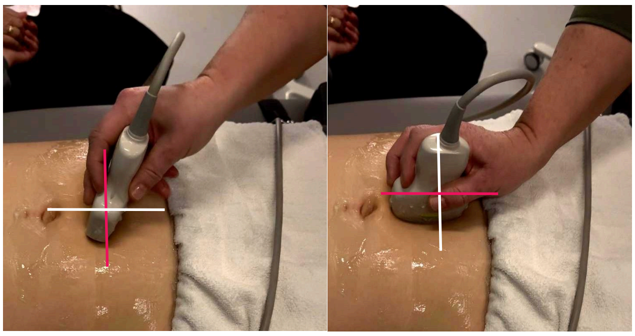


Figure 2.1c: 90-degree field

Movements of the probe

The researcher of this paper learned the technique of sonography during a visit to Fontys Hogeschool. In addition to rotating the probe, the following movements can be made to view the object at the correct angle:

- Rocking: move the transducer more in one direction than the other along the length of the probe.
- Tilting: move the transducer from side to side along the width of the probe.
- Fanning: involves holding one side of the probe and fanning or shifting the other side.

In Figure 2.1d, the author is depicted practising these movements.

Design Insights

The design must allow for the movements rocking, tilting and fanning which are shown in Figure 2.1d.

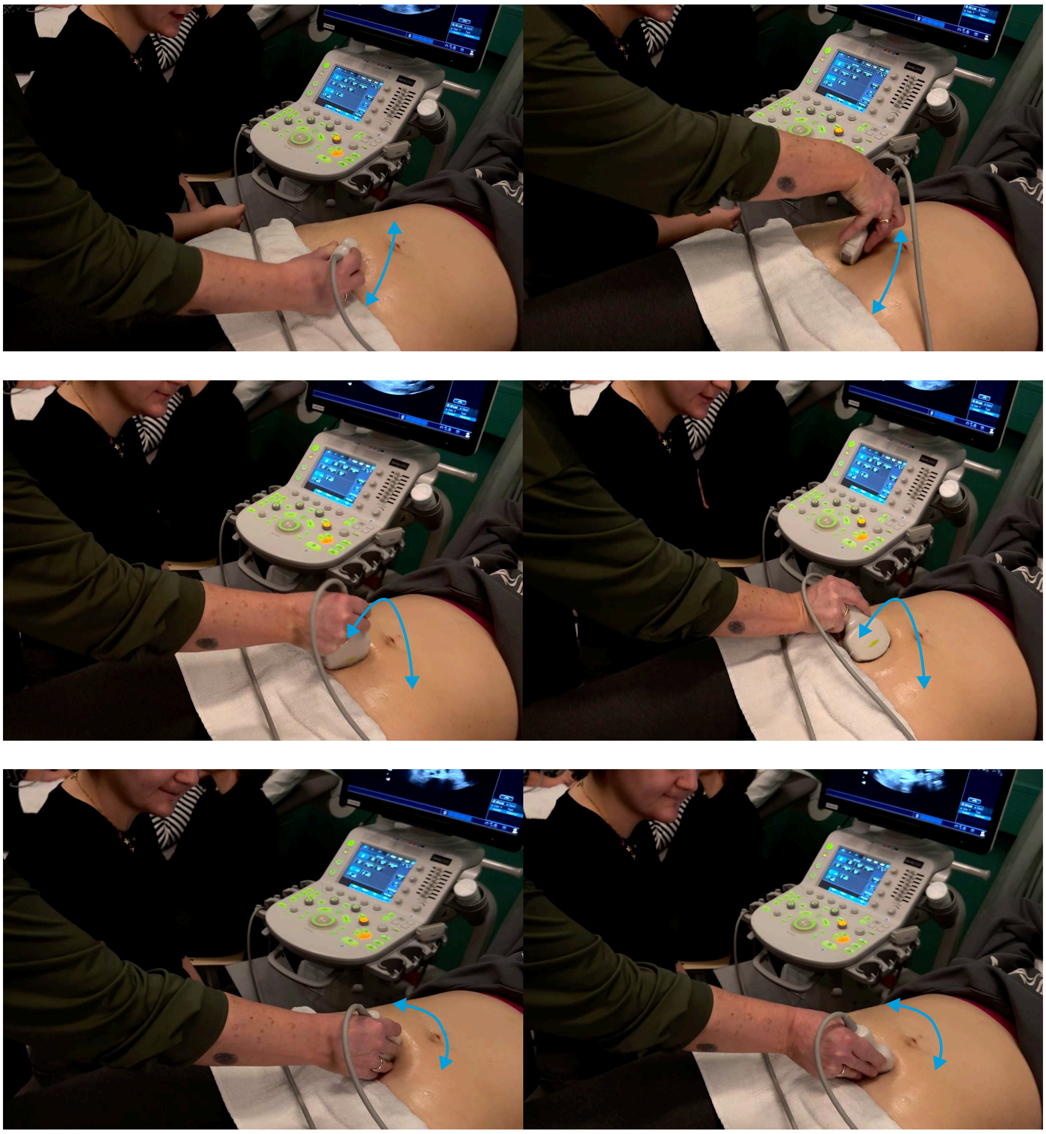


Figure 2.1d: Movement of probe. From top to bottom: Rocking, tiliting, fanning

2.2 Data collection through observation

Several observations were performed to understand the routine at both the paediatric department and the gynaecology department, and to find key insights contributing to WRMDs. The same method is used in both departments. The results are discussed separately.

2.2.1 Method

This observational study was conducted at the paediatric and gynaecology department of the RdGG. The goal of the study was to explore the workflow during ultrasound examinations. The researcher adopted a non-participant observational approach, remaining in the room during procedures but not taking part in any clinical activities. This approach was chosen in order to observe a situation that was as realistic as possible. Observations were carried out over a two-month period, during which ten ultrasound sessions were observed. Each session involved one patient and one healthcare professional.

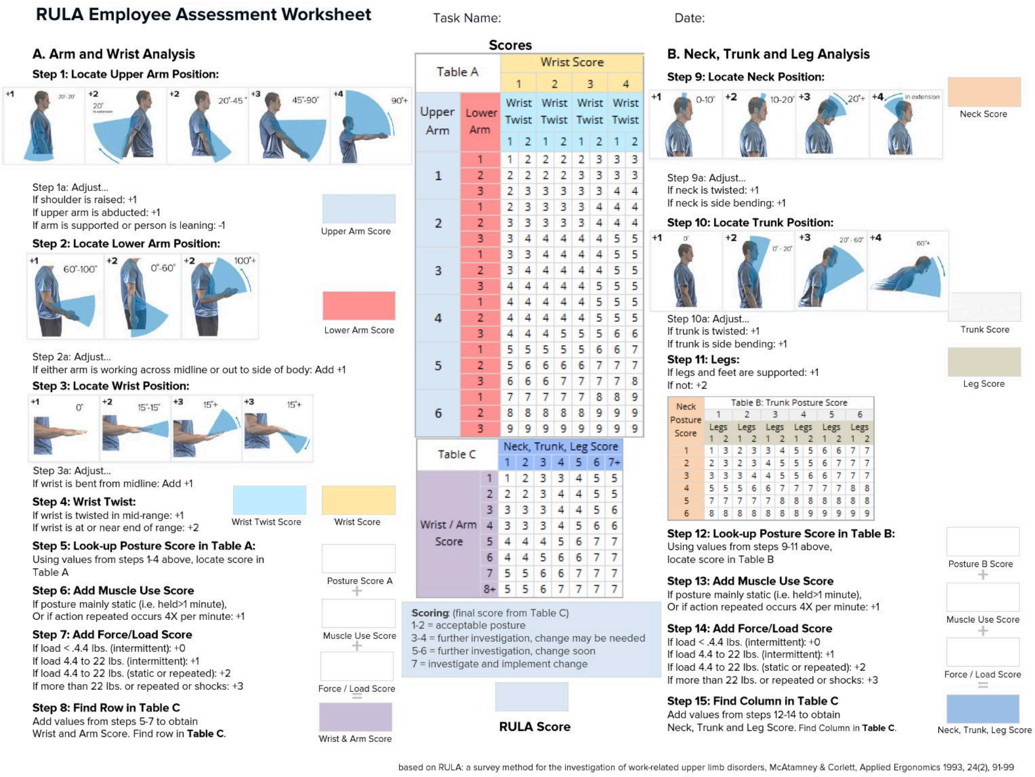
Field notes were taken in real time and focused on steps during the procedure, verbal communication, spatial arrangement, and use of equipment.

No audio or video recordings were made to minimise disruption and maintain patient privacy. However, several pictures were taken at the gynaecology department, but only with verbal consent of the patient and with the guarantee that the picture would be fully anonymous. The sonographers signed an informed consent forms, which document structure can be found in Appendix A.

The setup, patient positioning and movement are analysed and described. Next to this, a thematic analysis was conducted inspired by Braun and Clarke's (2006) six-phase framework.

Lastly, the RULA method is used to evaluate ergonomic risks associated with the upper extremities during the performance of the ultrasound. An example of the form can be found in Figure 2.2a. The hypothesis is that the postures far from the natural line, distal from the sonographer, score high on the RULA.

These three methods together give a structured and clear overview of the workflow and key insights that contribute to WRMDs.



RULA Employee Assessment Worksheet

Task Name:

Date:

A. Arm and Wrist Analysis

Step 1: Locate Upper Arm Position:

+1 20°-20° | +2 20° in extension | +2 20°-45° | +3 45°-90° | +4 90°+

Step 1a: Adjust...
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

Upper Arm Score

Step 2: Locate Lower Arm Position:

+1 60°-100° | +2 0°-60° | +2 100°+

Lower Arm Score

Step 2a: Adjust...
If either arm is working across midline or out to side of body: Add +1

Step 3: Locate Wrist Position:

+1 0° | +2 15°-15° | +3 15°+ | +3 15°+

Step 3a: Adjust...
If wrist is bent from midline: Add +1

Step 4: Wrist Twist:
If wrist is twisted in mid-range: +1
If wrist is at or near end of range: +2

Wrist Twist Score

Wrist Score

Step 5: Look-up Posture Score in Table A:
Using values from steps 1-4 above, locate score in Table A

Posture Score A
+

Step 6: Add Muscle Use Score
If posture mainly static (i.e. held>1 minute),
Or if action repeated occurs 4X per minute: +1

Muscle Use Score
+

Step 7: Add Force/Load Score
If load < .4.4 lbs. (intermittent): +0
If load 4.4 to 22 lbs. (intermittent): +1
If load 4.4 to 22 lbs. (static or repeated): +2
If more than 22 lbs. or repeated or shocks: +3

Force / Load Score
=

Step 8: Find Row in Table C
Add values from steps 5-7 to obtain
Wrist and Arm Score. Find row in **Table C**.

Wrist & Arm Score

Scores

Table A		Wrist Score 1		Wrist Score 2		Wrist Score 3		Wrist Score 4	
Upper Arm	Lower Arm	Wrist Twist 1	Wrist Twist 2	Wrist Twist 1	Wrist Twist 2	Wrist Twist 1	Wrist Twist 2	Wrist Twist 1	Wrist Twist 2
1	1	1	2	2	2	2	3	3	3
	2	2	2	2	2	3	3	3	3
	3	2	3	3	3	3	3	4	4
2	1	2	3	3	3	3	4	4	4
	2	3	3	3	3	3	4	4	4
	3	3	4	4	4	4	4	5	5
3	1	3	3	4	4	4	4	5	5
	2	3	4	4	4	4	4	5	5
	3	4	4	4	4	4	5	5	5
4	1	4	4	4	4	4	5	5	5
	2	4	4	4	4	4	5	5	5
	3	4	4	4	5	5	5	6	6
5	1	5	5	5	5	5	6	6	7
	2	5	6	6	6	6	7	7	7
	3	6	6	6	7	7	7	7	8
6	1	7	7	7	7	7	8	8	9
	2	8	8	8	8	8	9	9	9
	3	9	9	9	9	9	9	9	9

Table C	Neck, Trunk, Leg Score	1	2	3	4	5	6	7+
Wrist / Arm Score	1	1	2	3	3	4	5	5
	2	2	2	3	4	4	5	5
	3	3	3	3	4	4	5	6
	4	3	3	3	4	5	6	6
	5	4	4	4	5	6	7	7
	6	4	4	5	6	6	7	7
	7	5	5	6	6	7	7	7
	8+	5	5	6	7	7	7	7

Scoring: (final score from Table C)
1-2 = acceptable posture
3-4 = further investigation, change may be needed
5-6 = further investigation, change soon
7 = investigate and implement change

RULA Score

B. Neck, Trunk and Leg Analysis

Step 9: Locate Neck Position:

+1 0-10° | +2 10-20° | +3 20°+ | +4 in extension

Neck Score

Step 9a: Adjust...
If neck is twisted: +1
If neck is side bending: +1

Step 10: Locate Trunk Position:

+1 0° | +2 0° - 20° | +3 20° - 60° | +4 60°+

Trunk Score

Step 10a: Adjust...
If trunk is twisted: +1
If trunk is side bending: +1

Step 11: Legs:
If legs and feet are supported: +1
If not: +2

Leg Score

Neck Posture Score	Table B: Trunk Posture Score 1		2		3		4		5		6	
	Legs 1	Legs 2	Legs 1	Legs 2	Legs 1	Legs 2	Legs 1	Legs 2	Legs 1	Legs 2	Legs 1	Legs 2
1	1	3	2	3	3	4	5	5	6	6	7	7
2	2	3	2	3	4	5	5	5	6	7	7	7
3	3	3	3	4	4	5	5	6	6	7	7	7
4	5	5	5	6	6	7	7	7	7	7	8	8
5	7	7	7	7	7	8	8	8	8	8	8	8
6	8	8	8	8	8	8	8	9	9	9	9	9

Step 12: Look-up Posture Score in Table B:
Using values from steps 9-11 above,
locate score in Table B

Posture B Score
+

Step 13: Add Muscle Use Score
If posture mainly static (i.e. held>1 minute),
Or if action repeated occurs 4X per minute: +1

Muscle Use Score
+

Step 14: Add Force/Load Score
If load < .4.4 lbs. (intermittent): +0
If load 4.4 to 22 lbs. (intermittent): +1
If load 4.4 to 22 lbs. (static or repeated): +2
If more than 22 lbs. or repeated or shocks: +3

Force / Load Score
=

Step 15: Find Column in Table C
Add values from steps 12-14 to obtain
Neck, Trunk and Leg Score. Find Column in **Table C**.

Neck, Trunk, Leg Score

based on RULA: a survey method for the investigation of work-related upper limb disorders, McAtamney & Corlett, Applied Ergonomics 1993, 24(2), 91-99

Figure 2.2a: RULA form (Motmans, 2017)

2.2.2 Results Department of Paediatrics

Setup
The paediatric outpatient clinic has multiple rooms in which sonography examinations can be carried out. Figure 2.2b shows the room layout and the equipment used. The paediatric cardiologist sits on an ergonomic stool on the left-hand side of the examination table. This medical stool is designed by the brand Score for comfort during prolonged work.

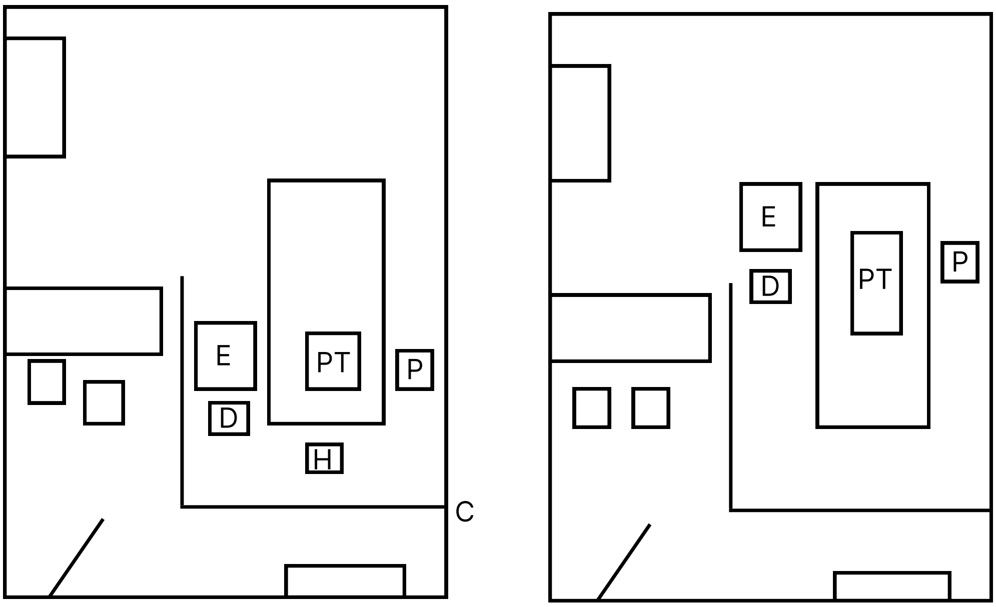
Probe S5-1 is most frequently used for sonography performed on babies and children between the age of 0-18 years old. For babies, a changing mat is used to ensure they are comfortable. For older children, a pillow is used to support the paediatrician's elbow. It depends on the growth of the child when it is switched to the other setup.

Finally, transmission gel is applied to the transducer to create a conductive layer. Figure 2.1b shows a map of the ultrasound room and how the patient is positioned for babies and older children. For babies in their first weeks, a heating lamp is used.

Figure 2.2b: Room setup and equipment used at the paediatric department

Design Insights

- *The design should not be limited to one room, as multiple ultrasound rooms are used.*
- *The design should be mobile to be used in both setups for babies and children.*



Legenda
E: Ultrasound equipment
D: Doctor
PT: Patient
P: Parent
H: Heating lamp
C: Curtain

Figure 2.2c: Map of room. On the left with a baby and on the right with an older child until the age of 18.

Patient positioning during sonography.
This procedure is formally known as a trans-thoracic echocardiogram (TTE). It is used to create an image of the heart. A detailed description of all the steps can be found in Appendix B.

During the procedure, the patient is asked to lie in two different positions: on their left side and on their back. Lying on their left side (also known as the left lateral decubitus (LLD) position) brings the heart closer to the chest wall, allowing better visualisation of the heart structures (Mitchell et al., 2018). The second position is lying on the back, also known as the supine position. This allows for a subcostal view (with the transducer placed under the sternum and angled upwards) and a suprasternal view (with the transducer placed at the base of the neck and angled downwards). See also Figures 2.2d and e. To facilitate the suprasternal view, a pillow is placed under the patient's back to tilt their head back and make room for the transducer, which is depicted in Figure 2.2f.

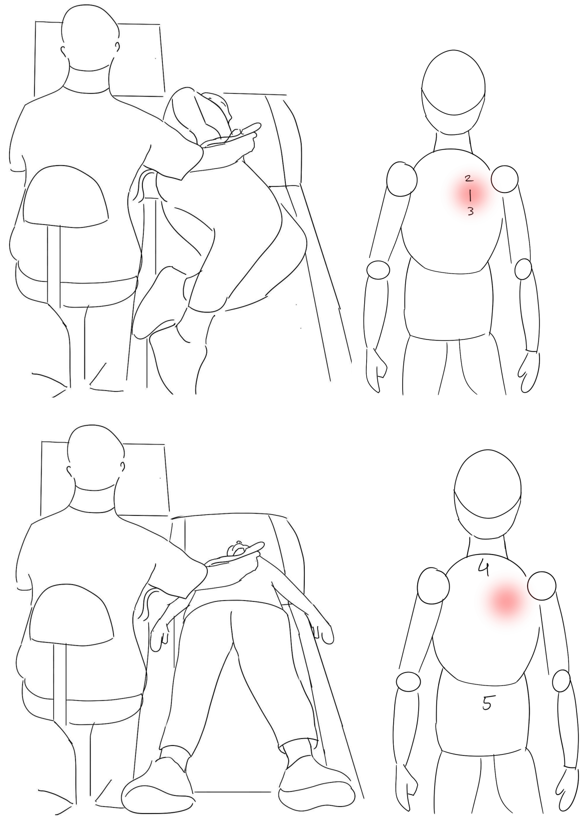


Figure 2.2d: Top: LLD position and probe placement.
Bottom: Supine position and probe placement

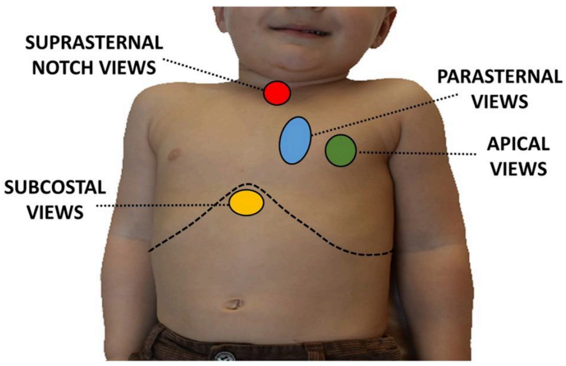


Figure 2.2e: Overview different views of the heart (Themes, 2021)

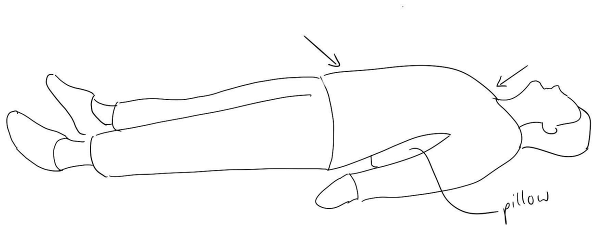


Figure 2.2f: Placement of pillow to make subcostal and parasternal view easier

Design Insights

- *The design must be usable in both LLD and supine position.*
- *The design should not limit the placement of the pillow underneath the patient in the supine position.*

Movement map

A movement map was made to illustrate the movements of the paediatrician while the patient is on the examination table. These movements need to be made according to the department-specific procedure; for a more detailed description, see Appendix C.

Each room has a different type of examination bed, but on average, they have a width of 650 mm. Sonography will be performed on children between the age of 0-18 years old. The map shows the placement of the probe for an older child, with the pink and blue circles describing the different positions in Figure 2.2g.

The patient is asked to move as close to the doctor as possible. To create a working field, the width and length of the patient's torso are important. Most children still want to lay their arms next to their torso when they are on the examination table. The breadth of the elbows can be found in DINED. The torso length is determined by looking at the shoulder height while sitting. This measurement is chosen as it is the only measurement available for children as well as for adults. Both measurements can be found in Figure 2.2h. This gives a maximum movement field with a width of 466 mm and a length of 612 mm (shown in dark blue in Figure 2.2g) and a minimum movement field with a width of 264 mm and a length of 335 mm (shown in red in Figure 2.2g).

populations	Dutch children 2, mixed	Dutch children 12, mixed	Dutch adults 18–30, mixed
measures	P50	P50	P50
Shoulder height, sitting (mm)	335	509	612
Breadth over the elbows (mm)	264	355	466

Figure 2.2h: Measurement of children and adults from DINED

Design Insights

- *The design should not limit the patient from moving as close as possible towards the sonographer.*
- *The patient must be able to lay their arm next to their torso.*
- *The design should provide movement sideways of 466mm and forwards/ backwards of 612 mm.*

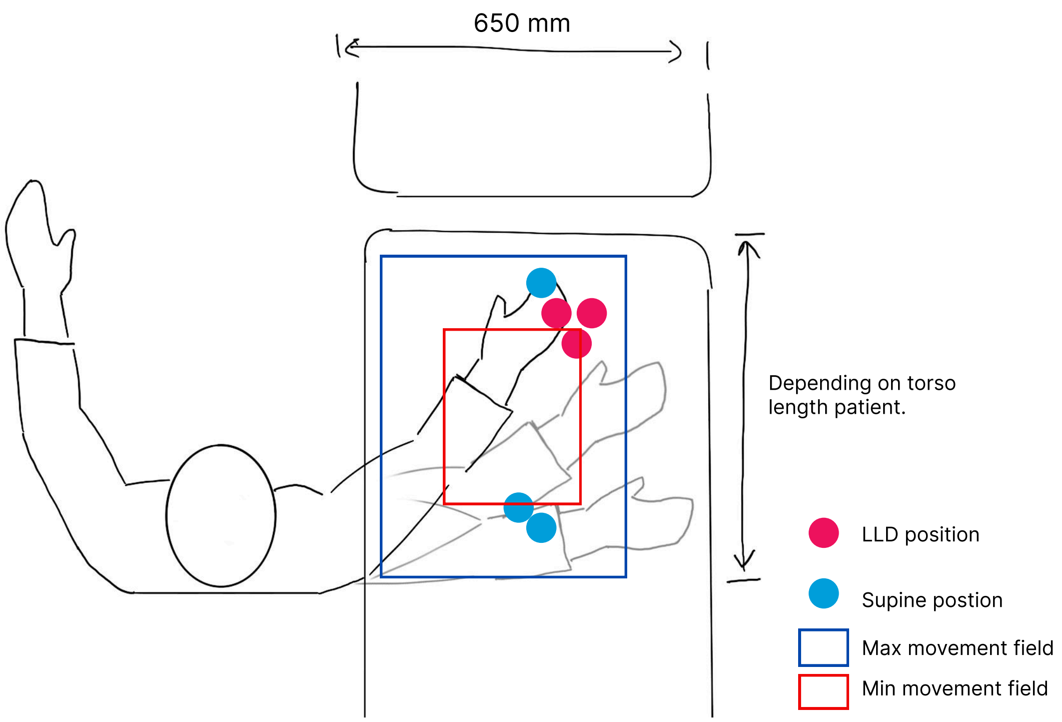


Figure 2.2g: Movement map showing probe placement (dots) and the minimum and maxium movement field

Theme clustering analysis paediatric department

The observations during the sonography were placed on post-its and clustered. This was done to discover underlying themes that show challenges and important parts of the procedure. The themes will be briefly addressed.

Deliver force

With corpulent patients, the doctor needs to deliver a lot of force to achieve a better image because you get a better image when you are closer to the heart. Next to this, children have firm abdominal muscles, causing them to have to push harder for the subcostal view. When you deliver the force, the grip around the probe is tightened.

Transducer movement

The probe is turned inside the hand and held in between the thumb and middle/ index finger to ensure control of the probe. In the LLD position, a pinch grip is used, while in the supine position, a normal grip is used to generate more force.

Interaction patient

The interaction with the patient is crucial to make the procedure more ergonomically, but this is also a challenge. For example the patient has to lie as close to the doctor as possible to make the arm abduct less. When children do not understand the question or do not understand the language, this can create a moment where the doctor will start the performance in an not optimal position due to time pressure. Sitting on the examination table next to the patient was not experienced nicely. At the cardiology department, they use a special table that has a bench built in. But this table is not for sale anymore.

Leaning as support

It is normal for the doctor to lean a little bit onto the patient. With babies, the wrist rests on the belly of the baby. With bigger children in the supine position, a cushion is used between the elbow and the patient to create support. This also helps create a barrier between the doctor and the patient, which can be unpleasant when a male doctor makes a scan of a teenage girl. The cushion slides away, sometimes not giving the optimal support.

Away from natural posture

The natural posture is not always present. In the supine position, the torso is rotated towards the patient. Next to this, with a baby, the arm is next to the torso, but the right shoulder is lifted. This could be fixed by lowering the table. Lastly, the wrist is out of the natural line when pressure is put on the abdomen.

Environmental influences

A baby of 8 months was observed who was really scared of the probe. She tried to push it away, obstructing the performance of the ultrasound. Next to this, crying and rolling will make it hard for the doctor to stay in an ergonomic position. Parents hold up their phone as a distraction, but also need to hold the baby still.

Design Insights

- *The design should not limit the doctor while applying force.*
- *A barrier between the patient and the doctor may be possible with teenage patients.*

RULA paediatric department

RULA (Rapid Upper Limb Assessment) is a method of assessing the risk of strain due to poor upper limb posture. Postures of shoulder, elbow, wrist, neck, trunk and lower limbs are taken into account. Each risk factor contributes to the overall score, where follow-up actions are suggested (Motmans, 2017).

The RULA is for only one posture, and therefore, two assessments are made for the doctor when the patient is in the LLD and supine position. The filled-in forms can be found in Appendix D.

RULA LLD position

The LLD position scores 6 points, stating that investigation is necessary and changes need to be made soon.

RULA supine position

The LLD position scores 7 points, stating that investigation is necessary and changes need to be implemented.

Conclusion and Limitations

Both the LLD and supine postures scored high on the RULA assessment (6/7 and 7/7), indicating a clear need for ergonomic improvements. The supine posture posed a higher risk due to a lack of arm support, greater wrist deviation, and increased exertion. These results suggest that providing adequate support could reduce physical strain and improve working posture, forming a strong basis for interventions.

Ergonomist G. Hoekstra has been consulted about this method. She mentioned the limitation that the RULA does not take time into account besides the muscle use.

Design Insights

- *Supporting the arm could reduce physical strain.*

2.2.3 Results Department of Gynaecology

In this paragraph, the results of the observational study will be discussed.

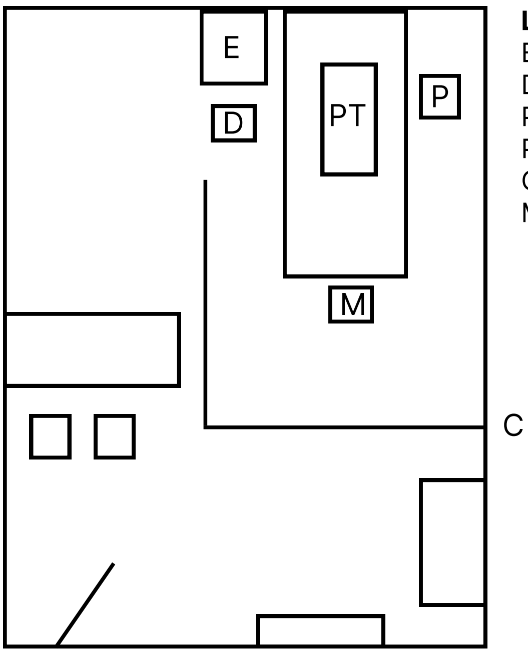
Set up
The gynaecology department also has several rooms for sonography. On the left side of the bed, the sonographer sits on a medical stool, also from the brand Score. The patient lies on the examination table (Renalchair series 410), which can be moved in several ways to create the mother's position where the baby is well visible on the sonograph. Other ultrasound rooms have different types of examination tables. A separate monitor is placed at the patient's feet so that both parents can see the sonograph on the monitor.

A GE C2-9 probe is used. The same transmission gel is used as in the paediatric department. Towels are placed between the skin and the patient's trousers to create an area where the sonographer can place the arm and protect it from the gel, as shown in Figure 2.2i. The room setup is illustrated schematically in Figure 2.2j.

Figure 2.2i: Set up and equipment at the gynaecology department

Design Insights

- *The design should not block the view between the patient and the monitor.*



Legenda
E: Ultrasound equipment
D: Doctor
PT: Patient
P: Partner
C: Curtain
M: Monitor

Figure 2.2j: Map of room. On the left with a baby and on the right with an older patient.

Positions of the patient during sonography
The whole procedure the patient is in a supine position. Sometimes the patient is asked to lie lower on the exam table so the hips can be tilted. This is asked so the baby will turn in a different position to make the area of interest easier to see.

It can occur that supine hypotensive syndrome occurs during the consultation. This occurs when the pregnant woman lies on her back, often during the third trimester. The weight of the uterus compresses the inferior vena cava and sometimes the aorta, reducing blood return to the heart. This can lead to a drop in blood pressure, dizziness and nausea (Massoth et al., 2021). Therefore, the patient will lie on her left side in the LLD position to prevent this from happening, as shown in Figure 2.2k.

Three extreme positions
For most of the patients, the heart lies in the same area. For the baby in the womb, on the other hand, the position can differ between patients even during the procedure. Every ultrasound is different, and other postures are needed. At the GUO, between 4-5 months, the baby lies between the belly button and the pelvis as shown in Figure 2.2l.

It is not possible to observe all the different postures with all the different baby positions, creating numerous postures to observe. Three extreme postures were chosen from the GUO procedure to analyse further:

1. Top: Placement of probe just underneath belly button, resulting in a floating elbow.
2. Distal Side: Reaching the other side of the belly, looking from above the baby.
3. Proximal Side: The Elbow is placed proximally to the body, and the torso is turned towards the patient.

Images of these positions as taken during an exam can be seen in Figure 2.2m.

Design Insights

- *The design should be as flexible as possible to enable smoothly switching between different postures.*

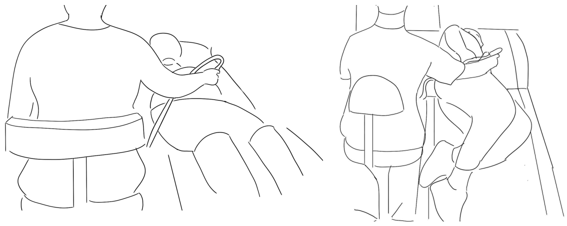


Figure 2.2k: Left: Supine position. Right: Left Lateral Decubitus

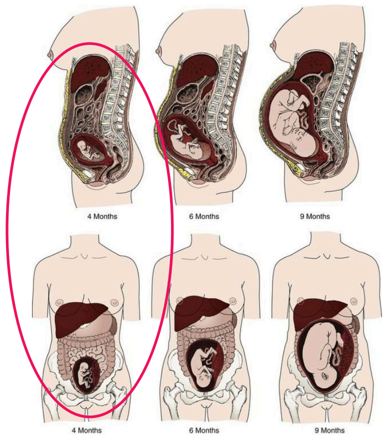


Figure 2.2l: Development op the baby in the uterus (Themes, 2016)

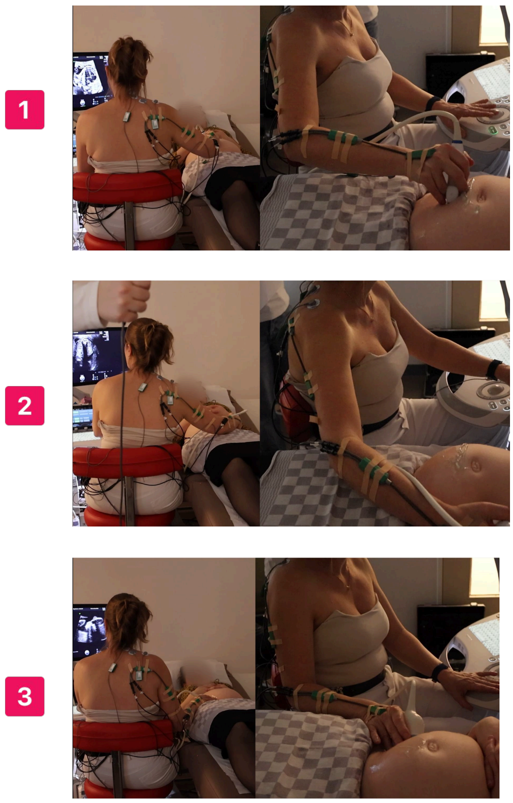


Figure 2.2m: Three extreme postures chosen for GUO procedure

Movement map
The same movement map as in paragraph 2.2.2 was created for the performance of the ultrasound at the gynaecology department. As explained before, during the GUO, the baby will be somewhere between the belly button and the pelvis. The gynaecologist looks at the baby from all angles. The map is based on the GUO observed during the EMG test, explained later in Section 2.3. The probe placement of a GUO is mostly on the lower half of the belly, shown with the pink circles. The width and length of the movement map depend on the measurements of the mother and the baby.

The fundal height in cm is measured from the pubic bone to the top of the uterus as shown in Figure 2.2n. The height is approximately the same as the gestational age in weeks, so 20 weeks equals +/- 20 cm fundal height. After 36 weeks, the relationship is less reliable. Based on the fundal height, the height of the movement map is between 120 and 380 mm. The width is determined by looking at the breadth over the elbows because the patient lies as close to the user as possible, but with the arm next to the body shown in Figure 2.2o. So the width of the movement map is between 412 and 508 mm max (DINED, n.d), see Figure 2.2p. Together, this yields a scan field as seen in Figure 2.2p.

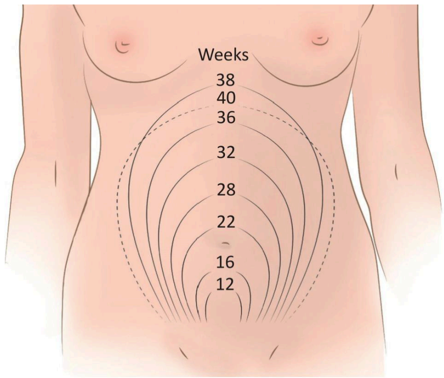


Figure 2.2n: Fundal heights plotted on belly

mean and sd	single measure	
populations	Dutch adults 20–30, female	Dutch adults 31–60, female
measures	P20	P80
Breadth over the elbows (mm)	412	508

Figure 2.2o: Table Breath over elbows (DINED).

Design Insights

- *The design should provide movement sideways of 508 mm and forwards/ backwards of 380 mm.*

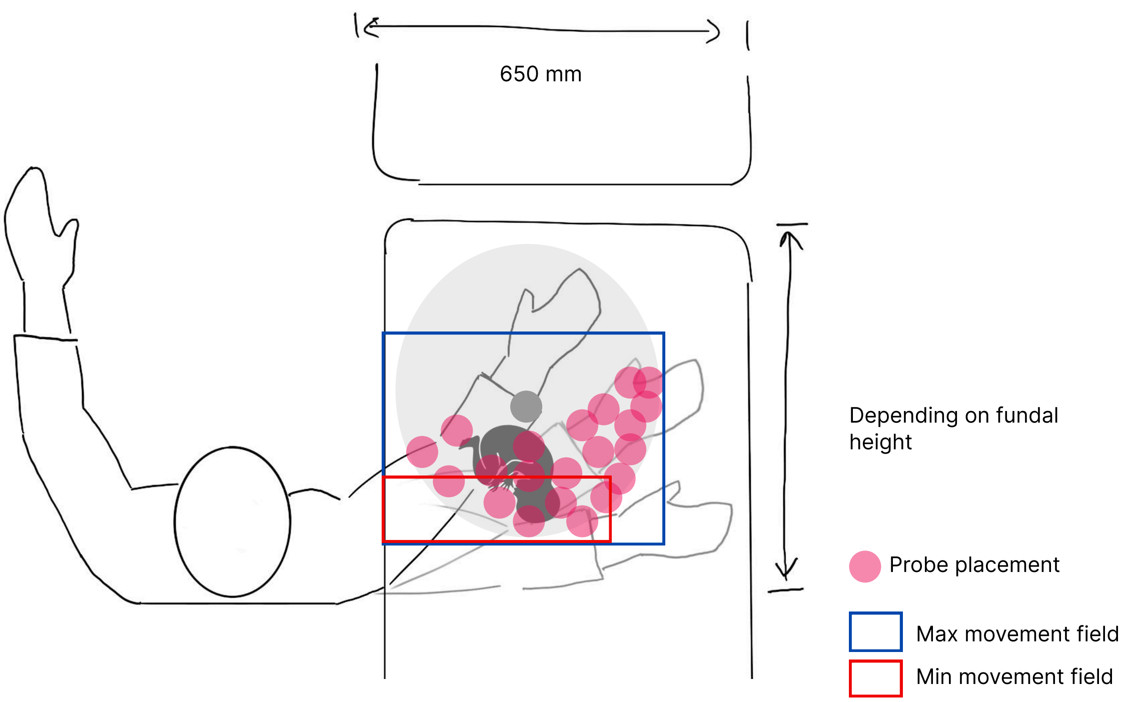


Figure 2.2p: Scanning posture and positions plotted on schematic belly

Theme clustering analysis gynaecology department
The observations during the sonography were placed on post-its and clustered. This was done to discover underlying themes that show challenges and important parts of the procedure. The themes will be briefly addressed.

Interaction patient
The procedure of sonography started with asking the patient to move as close as possible. During observations, it was noticed that when there was a language barrier, this was difficult. This was also the case when movement is difficult for the patient due to high pregnancy. There is a lot of physical contact with the patient due to leaning on the upper legs and belly. Lastly, there is collaboration with the patient necessary when the mother needs to position differently to make the baby move when it is in a difficult position for the ultrasound.

Preventative measures
The biggest preventative measures are asking the patient to lie close, setting up the equipment and leaning on the patient.
The gynaecologist mentioned that the right shoulder is pushed back to counteract the force that is given because the shoulder already hurts. This creates a twist in the torso towards the patient that causes other strains.

Same position for a longer time
To know where you are in the body of the baby during the ultrasound, the probe is held in the same position even at moments when a picture is taken or when you listen to the heart.

Difficult to mention pain
Because the focus is entirely on the performance of the ultrasound, the ergonomic posture is forgotten, and it is difficult to mention when the pain starts. The pain is felt in hindsight. While observing, the tension in the wrist can be seen. The pain was felt in the shoulder at the back and in the wrist

Flexibility vs control
The area to cover with the probe is way bigger than at the paediatric department. So a lot of flexibility is necessary. Simultaneously controlled movements are made with the probe while turning it in the hand, holding it in a pinch grip.

No support
When the patient is in de LLD position, the posture of the doctor is similar to the posture at the paediatric department when the patient is in the LLD position. It is not possible to lean on anything at this point because they dont use a pillow, and leaning on the belly may be uncomfortable for the patient on their side. When the patient is in supine position, when the probe is positioned around the belly button, the elbow floats.

Away from natural posture
A natural posture is when the joints are in their resting position and there is minimal stress on the muscles and tendons. Especially, the wrist joint is out of its natural line during the procedure. The elbow joint is turned open when the doctor needs to scan proximal to the belly. The back is bent over the patient when needed to reach the distal side of the belly. The torso is turned towards the patient. And lastly, the arm is abducted more than 30 degrees.

Good view on ultrasound
When the ultrasound is performed on a more corpulent patient, a lot of force is needed because you need to get closer to the baby in-between skin folds.

Design Insights

- *Both static and dynamic movements should be possible with the product.*
- *The product should promote a natural posutre.*

RULA gynaecology department
The RULA method is also used for the three extreme postures at the gynaecology department. The filled-in forms can be found in Appendix D.

RULA Top posture
Figure 2.2q shows the posture used for the RULA form. Filling in the form results in a four out of seven meaning investigation is needed, and changes may be needed.

Figure 2.2q: Extreme position 1, also the top posture in Figure 2.2m

RULA Distal Side
Figure 2.2r shows the posture used for the RULA form. Filling in the form resulted in a six out of seven, meaning investigation is needed, and changes are needed soon. The wrist, neck and trunk out of natural posture contribute to this higher score.

Figure 2.2r: Extreme position 2, also the middle posture in Figure 2.2m

RULA Proximal Side
Figure 2.2s shows the posture used for the RULA form. Filling in the form resulted in a score of six out of seven, meaning investigation is needed, and changes are needed soon.

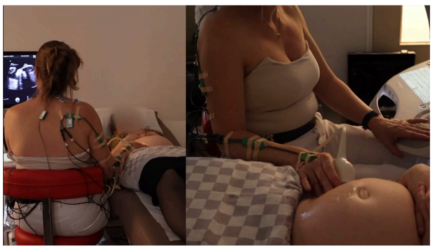


Figure 2.2s: Extreme position 3, also the bottom posture in Figure 2.2m

Conclusion and limitations
As expected, the distal and proximal posture score higher on the RULA because the body of the doctor is out of the natural line. This shows that it is important that the design is not only made for the posture in the middle of the belly but also accommodates the extreme, as these score higher on the RULA.

One of the limitations is that the RULA does not incorporate the time holding the posture. Therefore, holding the posture for 5 minutes or 45 minutes gets the same score. However, it does take into account whether the posture was static or repeated motions.

Design Insights

- *Design should support the arm in all the outer postures.*

2.1.4 Conclusion on design insights

The design insights gathered through observations in the paediatric cardiology and gynaecology departments have revealed the complex, multifactorial nature of WRMDs in sonography.

A key takeaway is the need to balance flexibility and control within the design. The recurrence of unnatural postures caused by the interaction between the sonographer and patient reinforces the necessity of ergonomic support, particularly for the arm in extreme positions.

Furthermore, the design must seamlessly fit into existing workflows, allowing practices like applying gel and accommodating the use of items such as heating lamps and changing mats. It must also adapt to changing room setups, support both LLD and supine positions, and avoid interfering with pillow placement or proximity between the patient and sonographer. Additionally, it should support a wide range of arm movements, between 466-508 mm sideways and 380-612 mm forward/backwards.

To be viable, the product must be mobile, fit multiple rooms, promote a natural posture, and not hinder communication, visibility, or procedural speed. Ultimately, the success of the design will depend on its ability to reduce physical strain without disrupting the flow and demands of the procedure.

2.3 Data collection through EMG test

An electromyogram, in short EMG, is a research method used to measure the muscle voltage to evaluate the muscle activity. For this project, it is used to see what the muscle activity is during sonography and how the muscles' activities are affected by each posture. Next to EMG, goniometers are used to register the angles of the shoulder and wrist during the different postures. The goal is to register the activity and angles and see what postures require the most labour of the muscles. From that, requirements for the to-be-designed instrument can be set concerning how it should support the user in those postures.

The hypothesis is that EMG results will show lower muscle activity when using the proposed support tool compared to the status quo. Wong et al. (2021) demonstrated that reduced muscle activity contributes to minimising overall muscle fatigue. In addition, a delayed onset of muscle fatigue is also expected. The same study showed a significant reduction in supraspinatus stiffness when the scanning arm was supported, across all abduction angles tested, suggesting that support not only lowers effort but also prolongs endurance.

2.3.1 Method

Participants selection
Two participants were recruited through the hospital. They were chosen because they experience WRMDs from performing ultrasounds in their departments, which made it easier to explain the purpose of the test to them. One participant is a sonographer in the paediatric department, and the other is a sonographer in the gynaecology department. The simulation patients were recruited either via personal connections or through the hospital among staff. In the gynaecology department, the simulation patient had to be around 20 weeks pregnant, and in the paediatric department, the participant had to be male and slim. A male was chosen because the simulation patient had to be topless for the procedure, making it easier to film with a male participant.

Setup and Materials
The tests took place at the RdGG in the ultrasound room at the paediatric and gynaecology department. The setup of the test is shown in Figure 2.3a. A simulation patient was used to make the test as realistic as possible. A simulation patient is a volunteer who is not a patient of the sonographer. The patient already knows that they are healthy. The cameras were used to capture the test from two angles to later cross-reference the EMG data with the different postures. The computer was used to record the EMG data.

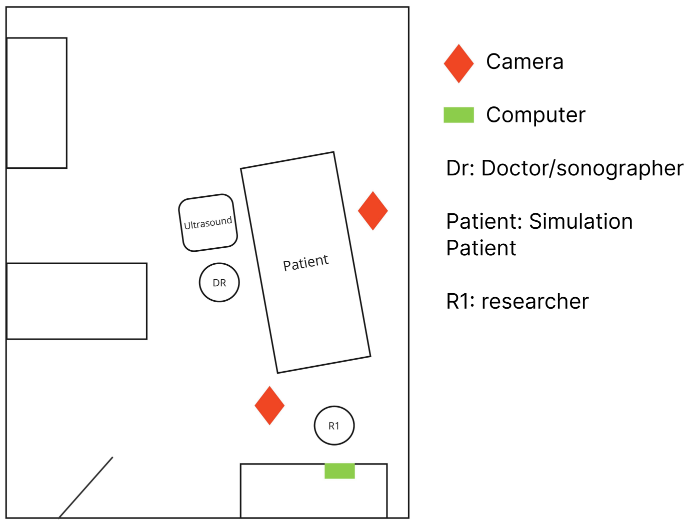


Figure 2.3a: Setup in Ultrasound room

Three muscles were observed: the supraspinatus, upper trapezius, and flexor digitorum profundus. They were chosen based on pain-prone areas identified in Section 1.5 and illustrated in green in Figure 2.3b.

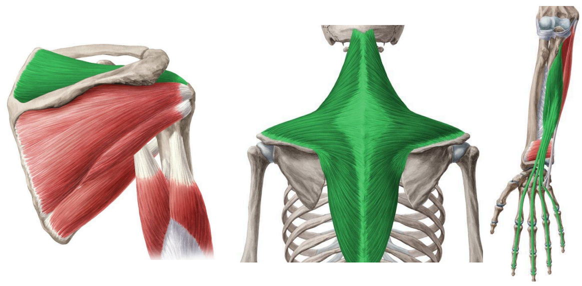


Figure 2.3b: Left to right: supraspinatus, trapezius, flexor (Human Anatomy, 2023)

The supraspinatus and trapezius support arm abduction, a movement identified as a risk factor (Lam & Bordoni, 2025).
The flexor digitorum profundus was included to assess wrist and finger flexion during ultrasound tasks, particularly under applied pressure on the probe.

EMG measurements were conducted using a Biometric EMG set borrowed from the Human Factors Lab at Industrial Design. The system, detailed in Appendix E, included EMG sensors placed according to guidelines from the *Anatomic Guide for Electromyographers*, adapted for snap-on electrodes (Figure 2.3b). Electrodes were placed at the start and middle of each muscle to capture signal variation. Goniometers were attached on both sides of the shoulder and wrist joints (see Figure 2.c) using medical tape to prevent shifting. A button connected to the computer was used to log posture changes, and data were recorded via a laptop and two cameras.

Procedure
The participants were asked to perform the ultrasound on the simulation patient as they would normally do at their department. For the gynaecology, this is the GUO and for the paediatric, the full check-up of the heart as explained in Section 1.4.

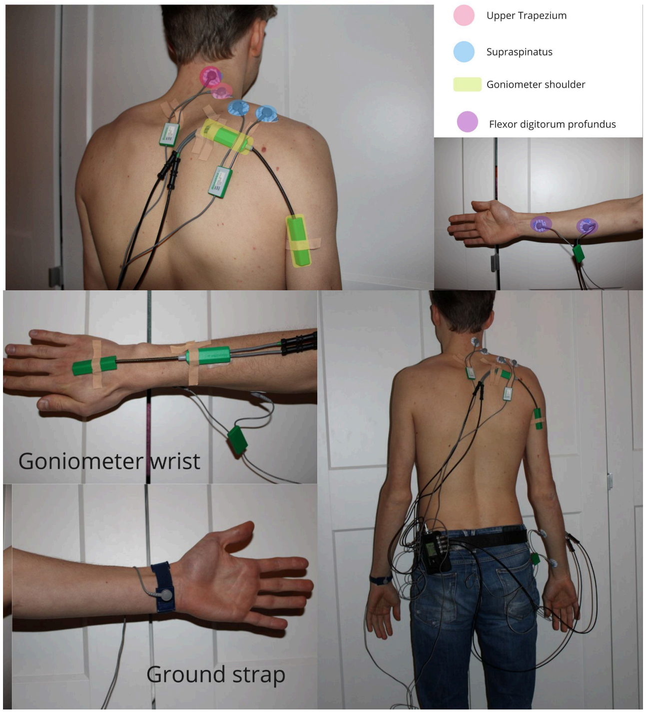


Figure 2.3c: Placement of EMG sensors and goniometers

Participants were asked to think aloud and indicate posture changes. When they changed posture or something unexpected happened, the button was pressed.

Any discomfort was marked by the researcher on a comfort map shown in Appendix E. The full test plan is included in Appendix E, with the procedure described in more depth.

Ethics
All participants were asked to sign an informed consent, including the following statement, to give their preference about being in pictures:

I give permission for using photos of my participation:
(select what applies for you)

- *In which I am recognisable in publications and presentations about the project.*
- *in which I am not recognisable in publications and presentations about the project.*
- *for data analysis only and not for publications and presentations about the project.*

The general document structure for the informed consent form can be found in Appendix A.

Next to this, all demographic information will be noted anonymously with only the participant ID. The test was conducted in a closed-off ultrasound room to prevent someone stepping into the room by accident and finding the participants partially bared.

Analysis of data
The data of the EMG and goniometers are exported with the AC2 filter on and denoted in engineering units. The resulting text file was analysed using a script in MATLAB that can be found in Appendix F. The graphs were analysed next to the video taken to see which postures entail more muscle activity. Next to this, we looked at the angles that correspond with these postures.

When analysing the EMG results, caution has to be taken when comparing different muscles or even different test results from the same muscle. Different muscles have different maximum strengths, and thus different maximum voltages over them. Moreover, as the measurement of the voltage is very dependent on the circumstances, it makes comparing different tests of the same muscle quantitatively impossible. Fatty skin, body hair or a slightly differently placed electrode patch can all impact the found voltages. As these factors cannot be accurately reproduced, the analysis of the EMG remains qualitative.

For the goniometers, the 0 degree point corresponds with a natural relaxed position, so with the arm straight down along the torso, and for the wrist in a neutral position in line with the underarm.

As the right shoulder was analysed, a negative amount of degrees corresponds to an abduction, so counter-clockwise when seen from the back. Thus, a number of -90 degrees matches the right arm stretching horizontally to the right. For the wrist, flexion and extension correspond with positive and negative values, respectively. As opposed to the EMG results, the goniometers' outcome can be compared over the various tests. This can be both quantitative and qualitative. Figure 2.3d shows the anatomical movements described above.

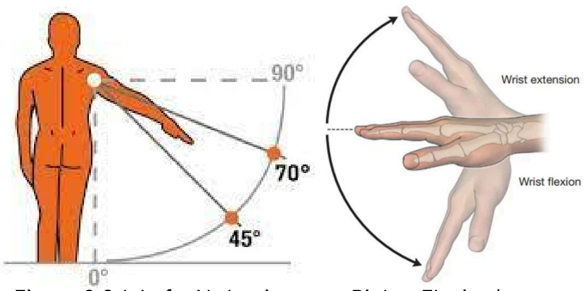


Figure 2.3d: Left: Abduction arm, Right: Flexion/ extension wrist

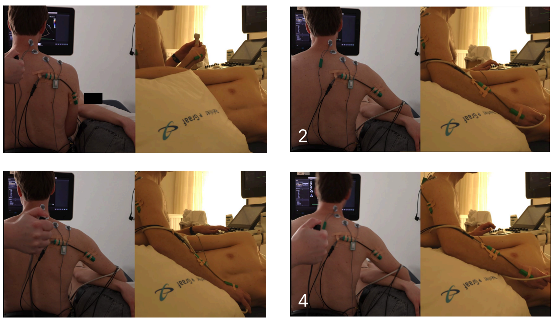


Figure 2.3e: Four moments the button was pressed.

2.3.2 Results LLD position paediatric department

Due to battery failure, the test at the paediatric department was split into two parts of the two postures: left lateral decubitus (LLD) and supine position. Therefore, the results of these positions are discussed in two separate paragraphs.

Findings

The button was pressed four times, representing four posture changes of the participant. The battery failed, so the measurement ended abruptly. Figure 2.3e shows the four times the button was pressed. These four postures were analysed for each of the muscles.
The most interesting results are discussed in the following subparagraphs: abduction, supraspinatus, trapezius and flexor. These are kept the same with all tests to enable comparison between the tests.

Abduction

As was mentioned in Chapter 1, arm abduction greater than 30 degrees is a risk factor for WRMD. Figure 2.3f shows the abduction/adduction of the shoulder for the whole LLD part of the examination, with the numbers depicting the different parts. The blue box represents the abduction area. The black line represents the 30-degree mark. As shown in Figure 2.3f, for 96% of the time, the abduction is greater than 30 degrees.

Note that the right y-axis depicts the angle of abduction/adduction (or flexion extension for other measurements). This is in correspondence with further plots, where we will have the EMG results on the left axis.

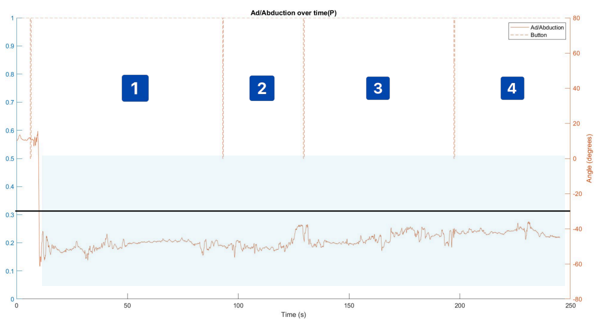


Figure 2.3f: Ad/Abduction plot LLD paediatric ultrasound

Supraspinatus

In the LLD position, the supraspinatus is quite active. The biggest peaks are seen when changing from position, as the arm is then lifted. Figure 2.3g shows an area circled where you see a lot of 'transient' activity. That is, when compared to the first parts of posture 3 and 4, the muscle is not relaxed. Thus, the muscle is performing a lot of work, whereas the arm is not moving all too much. The latter can be seen from the relatively flat goniometer results around 50 degrees of abduction. This activity could be due to pushing the transducer and the abduction that is above 30 degrees, making the muscle work hard to keep the arm in this position. The encircled area corresponds with the pose as depicted in Figure 2.3h.

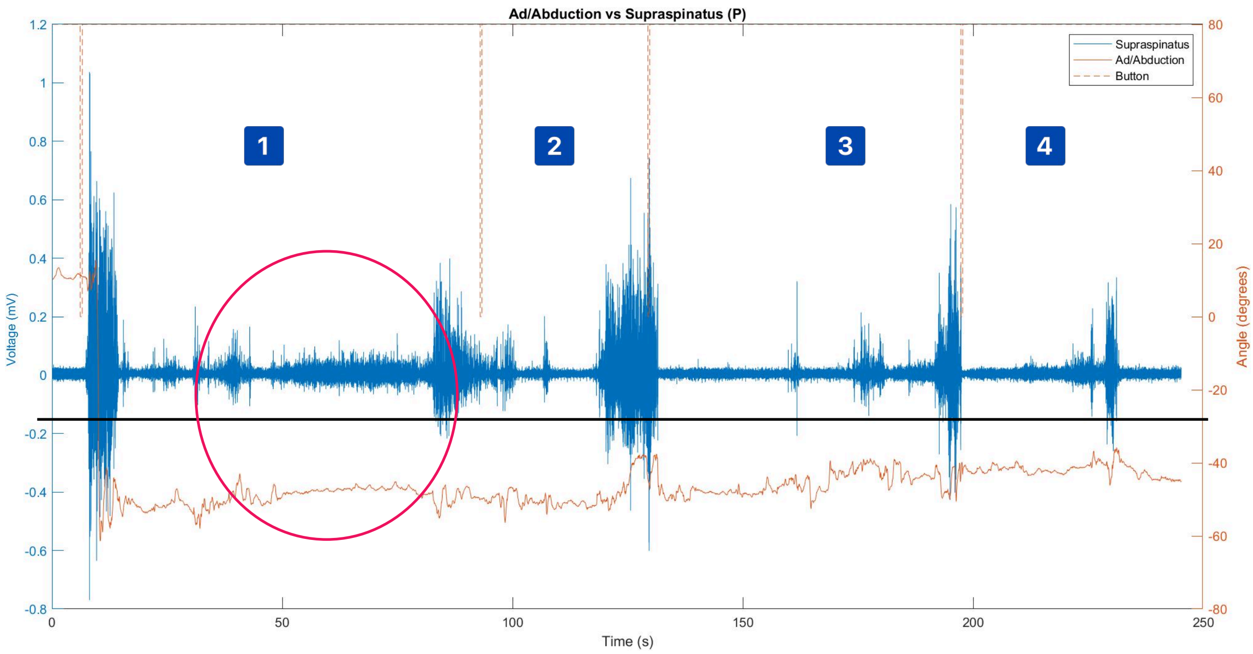


Figure 2.3g: Muscle activity of supraspinatus plotted against ad/abduction with transient activity encircled.

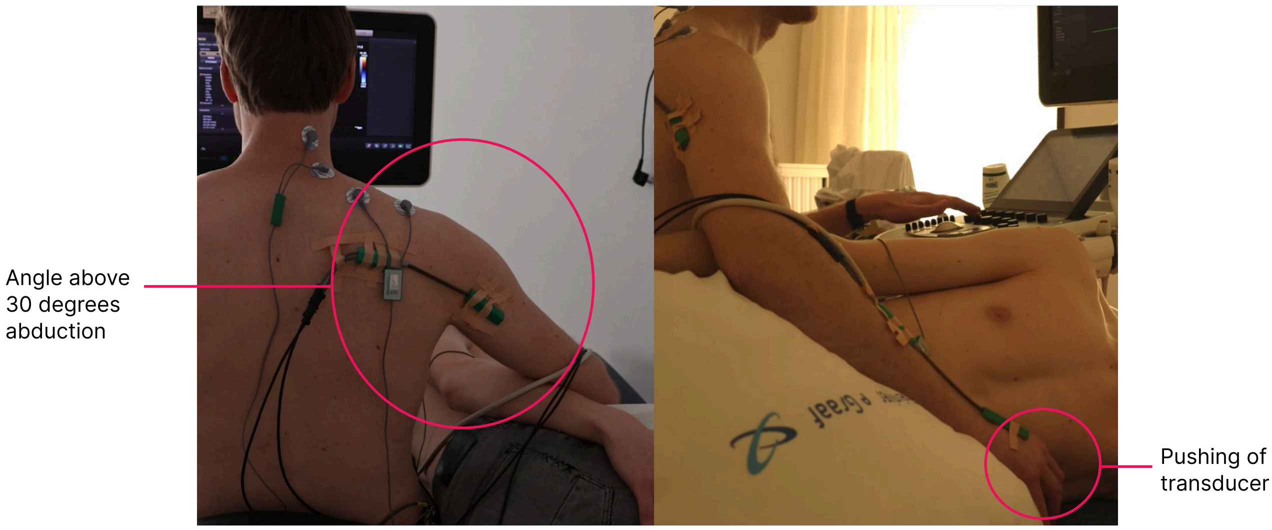


Figure 2.3h: Picture of the moment with transient activity in supraspinatus.

Trapezius
In the LLD position, the trapezius is quite active but stable for the entire test. The biggest peaks are seen when changing from position as the arm is lifted. See Figure 2.3i below, around where the button is pressed.

Flexor
In the LLD position, the flexor profundus activity is continuous. In the first and second postures, there is some extension of the wrist up to 30 degrees. In the third and fourth postures, there is more flexion: up to 50 degrees, as can be seen in Figure 2.3j.
It also shows increased muscle activity in the third and fourth postures, indicating the grip and force put on the probe.

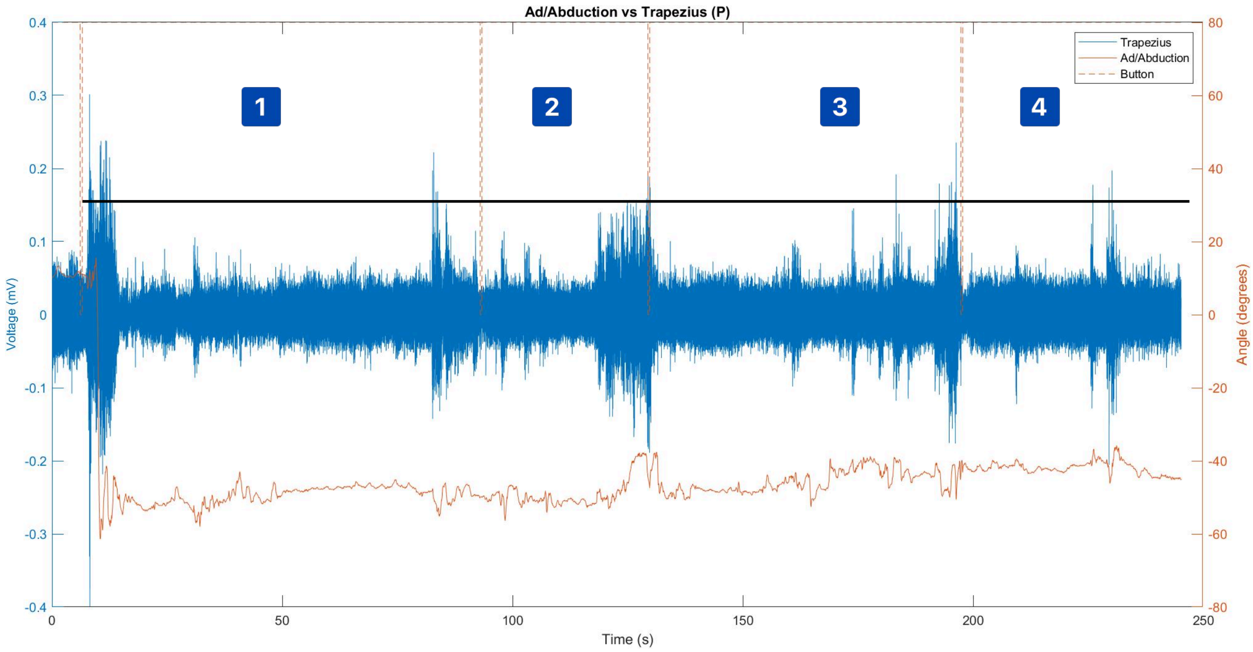


Figure 2.3i: Muscle activity of trapezius plotted against ad/abduction

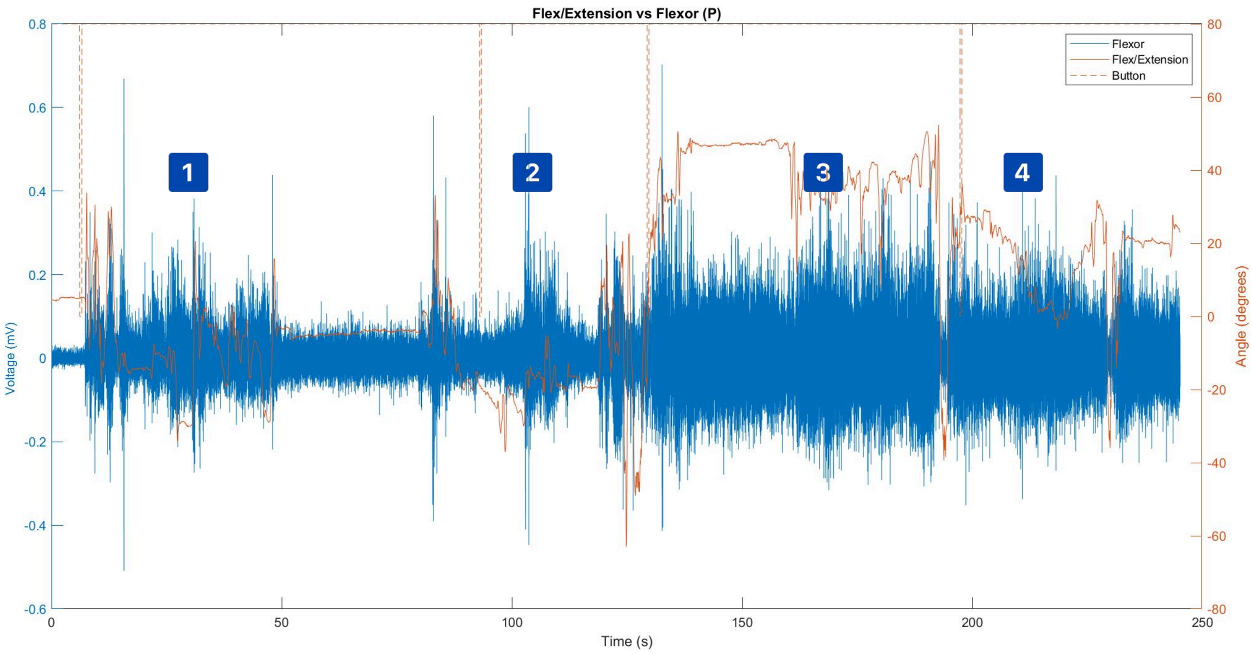


Figure 2.3j: Muscle activity of flexor plotted against flex/extension

2.3.3 Results supine position paediatric department

This paragraph describes the results from the paediatric department when the patient is in the supine position.

Findings paediatric department supine position
The button was pressed four times, representing three postures of the participant. The button clicked at the finish is not a new posture, so 3 postures will be analysed. Figure 2.3k shows the four times the button was pressed, including the start and the end. These three postures were analysed for each of the muscles. The most interesting results are discussed hereafter.

Abduction
Figure 2.3l shows the abduction/adduction of the shoulder muscle. The blue box represents the abduction area. The black line represents the 30-degree mark. As shown in Figure 2.4l, for 50% of the time, the abduction is greater than 30 degrees.

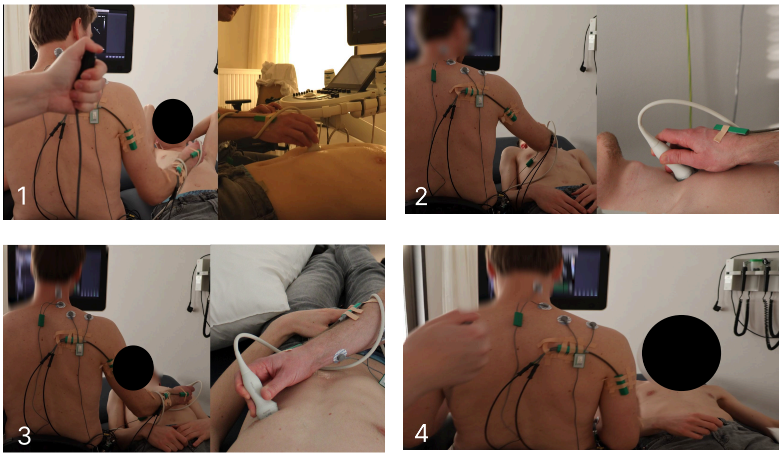


Figure 2.3k: The four moments the button was pressed with 1-3 showing the three different postures.

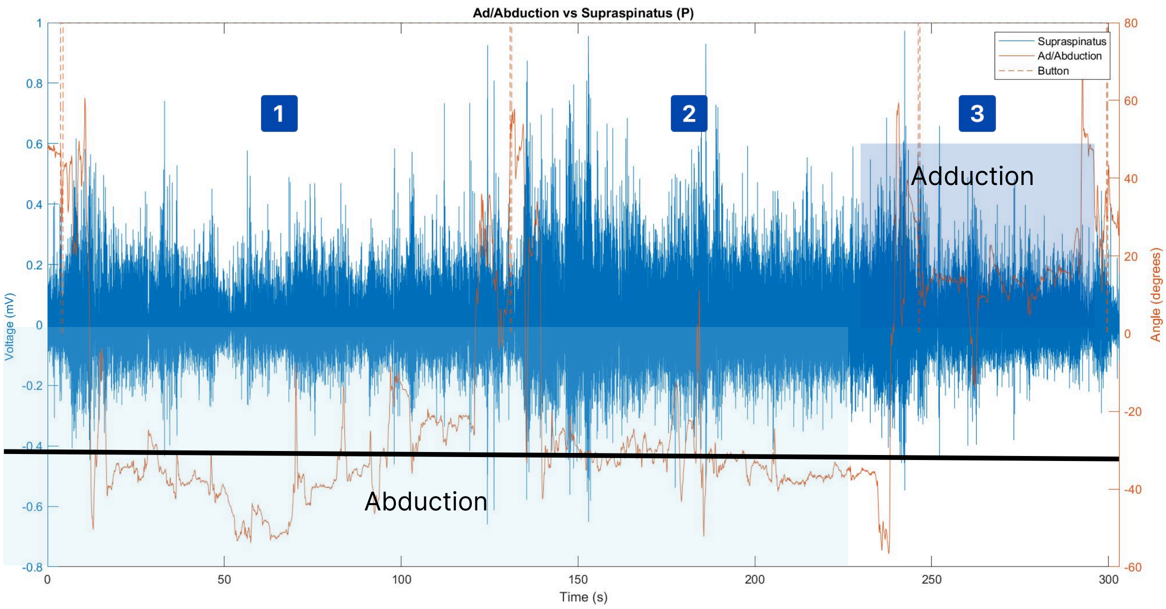


Figure 2.3l: Muscle activity of supraspinatus plotted against ad/abduction.

Supraspinatus
In the supine position, the supraspinatus is a lot more active. This was also expected because during the LLD position, it was possible to lean on the cushion. In the supine position, the elbow is floating (illustrated in Figure 2.3m), causing the supraspinatus to work harder to keep the arm abducted. In the first position, the participant had to use a lot of force on the patient due to the distance between the probe and the heart.

In the second position, the arm is abducted and also flexed to reach the front of the torso. In this position, the supraspinatus has to work really hard, which results in a lot of muscle activity shown in Figure 2.3k on the previous page. This position had to be held for ca. 2 minutes.

Figure 2.3m: One of the postures for supine position, with the elbow clearly elevated above the patient.

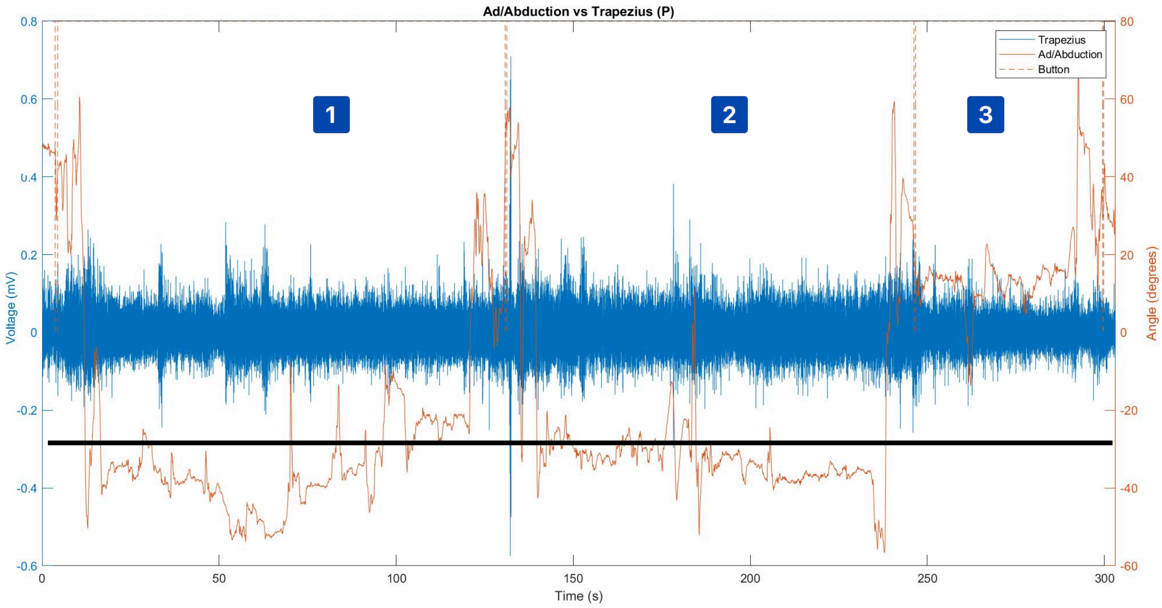


Figure 2.3n: Muscle activity of trapezius plotted against ad/abduction.

Trapezius
In the supine position the trapezius is active but stable the entire part. This is seen in Figure 2.3n.

Flexor
The flexor was not measured in later tests. An in-depth analysis of this test is therefore moved to Appendix G.

Pain moments paediatric department
The positive effect of using the thinking out loud method was that multiple remarks were recorded when the sonographer mentioned pain. These moments are discussed for the two different positions of the simulation patient.

Pain was mentioned during the LLD position patient
After holding the probe over 4 minutes, the participant mentioned pain on the inner side of the hand underneath the thumb (see Figure 2.3o), rated a 3/10. This group of muscles is called the thenar eminence, and pain can be caused by repetitive movements (Morrison, 2024).

Figure 2.3o: Top: Visual of participant's reported pain point (Dr. Kuypers Kliniek, 2024). Bottom: accompanying posture of hand.

Pain was the mentioned durthe ing supine position patient
When the patient is in the supine position, the participant starts by applying force to the abdomen. After 50 seconds, the participant mentioned again the thenar eminence, now giving it a score of 5/10, showing it needs to grip harder when applying more force.

Consequently, after applying force to the abdomen for over 2 minutes, a cramp is mentioned in the hand on a scale of 3/10, the posture is depicted in Figure 2.3p. The marks of the force can be seen on the simulation patient his body (see Figure 2.3q).

The thenar muscles are responsible for the fine movements of the thumb and are crucial for gripping objects (Luxenburg & Rizzo, 2023). It is observed that when the user grips too hard, this causes muscle strain.

Figure 2.3p: Picture of posture of hand when cramp was experienced.

Figure 2.3q: The force marks on the simulation patient.

2.3.4 Results gynaecology department

In this paragraph, the results of the test at the Department of Gynaecology are discussed.

Findings

The button was pressed 43 times, indicating numerous posture changes by the participant (see Figure 2.3r). These changes consisted of both large and small movements. A detailed list with explanations of all 43 button presses can be found in Appendix H. Due to the variety of postures, the same three extreme postures from the RULA were again used to analyse the different muscles. Figure 2.3s shows the three postures that are already discussed in Section 2.2.

These three postures will be analysed on abduction and their muscle activity.

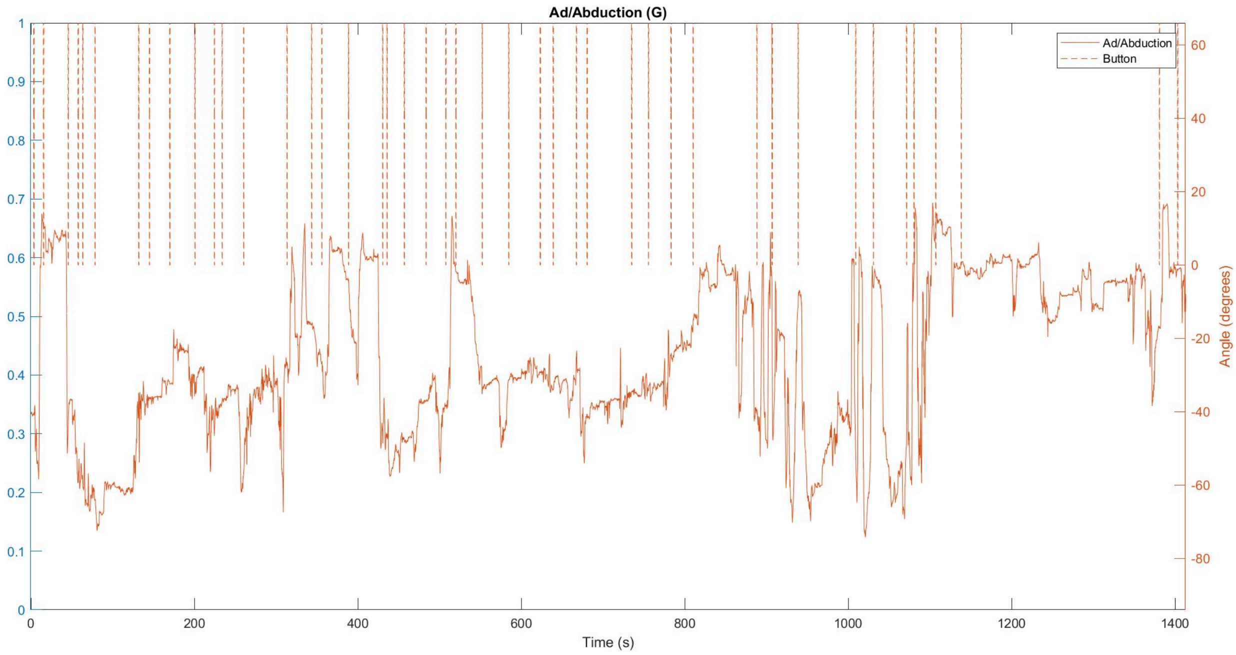


Figure 2.3r: 43 posture changes plotted against the ab/adduction

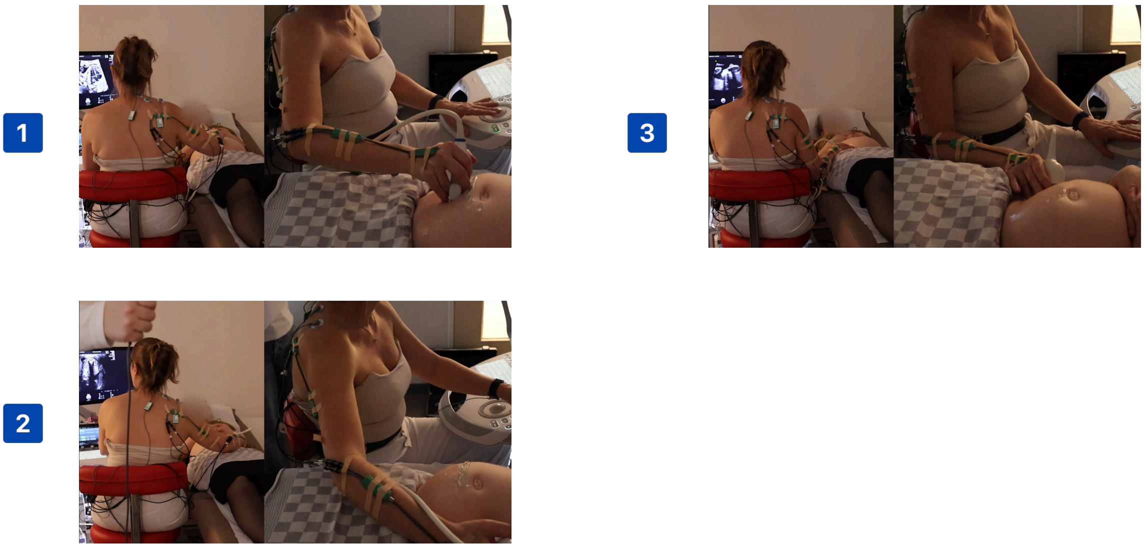


Figure 2.3s: Three extreme postures at the gynaecology department

Abduction

Figure 2.3t shows the activity of the supraspinatus and the abduction/adduction of the shoulder. The biggest part is abduction, with the 0 being the elbow next to the torso. The black line represents the 30-degree abduction. The figure shows that 54% of the time, the arm is more than 30 degrees abducted, with a few moments reaching almost 80 degrees. The abduction is coloured in light blue.

In the first position, the abduction is a little over 30 degrees. However, the second position (illustrated in Figure 2.3u) is an extreme position with reaching 80 degrees of abduction. In the third position, the arm is next to the torso with almost no abduction, even going towards adduction as the torso is turned towards the patient.

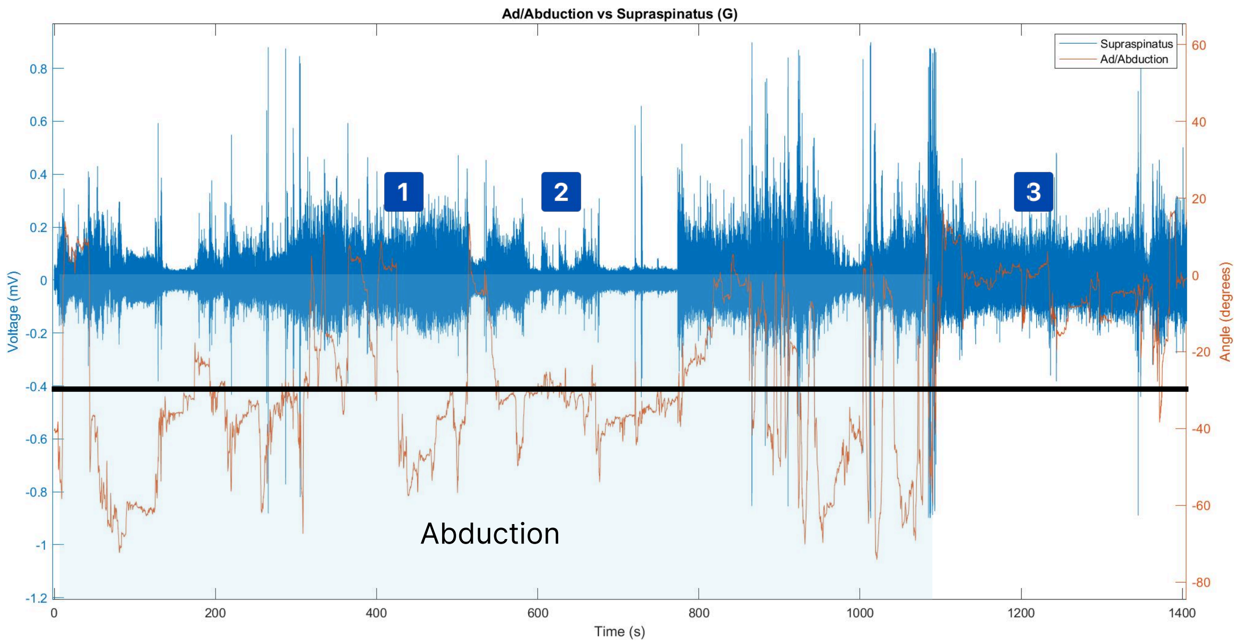


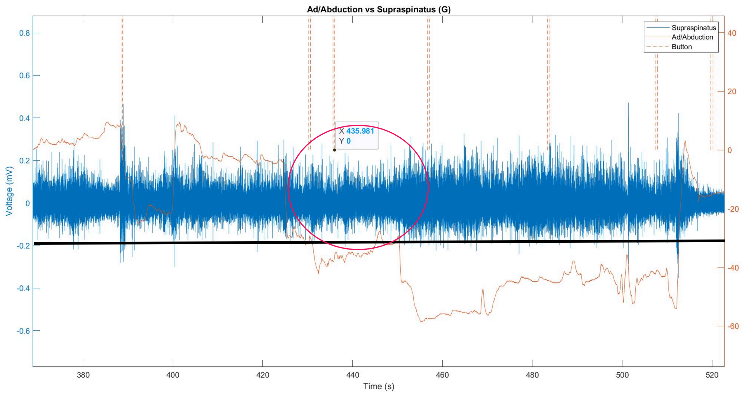
Figure 2.3t: Muscle activity of supraspinatus plotted against ad/abduction

Figure 2.3u: Most abduction in posture 2 when the upper right side belly needs to be reached

Supraspinatus

Figure 2.3v.1-3 shows the activity of the supraspinatus muscle and the abduction/ adduction of the shoulder. These plots are zoomed-in versions of Figure 2.3t, see the accompanying number icons. The corresponding postures can be found in Figure 2.3w.1-3. In the first posture, the elbow is in a floating position, showing muscle activity with peaks of up to 0.2 volts. In the second posture, the arm is supported by the upper legs. Although the abduction is the same in both postures, the supraspinatus is less active. In the third posture, the supraspinatus is less active due to the arm being next to the torso.

1



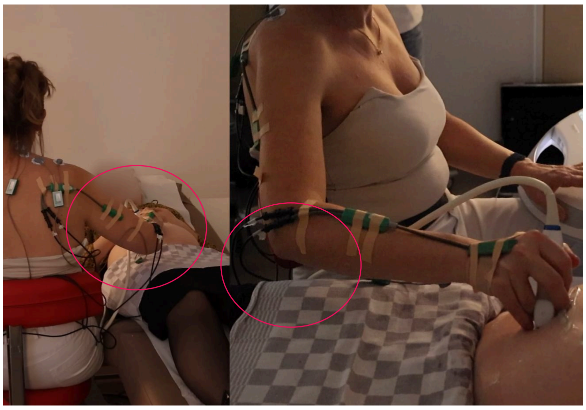


Figure 2.3v.1: Muscle activity supraspinatus with posture one encircled. Figure 2.3w.1: Posture one with floating elbow circled

2

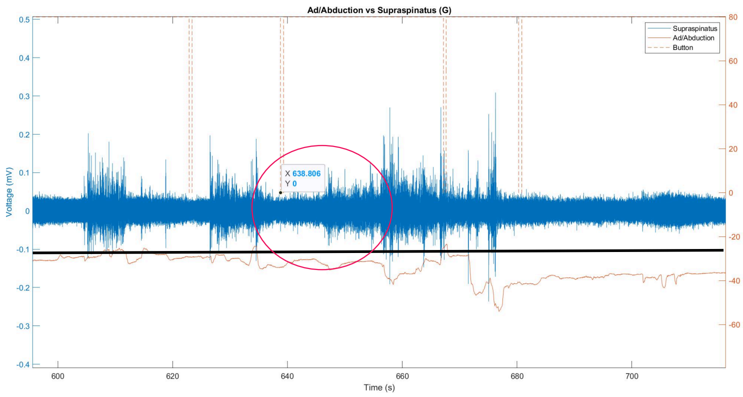
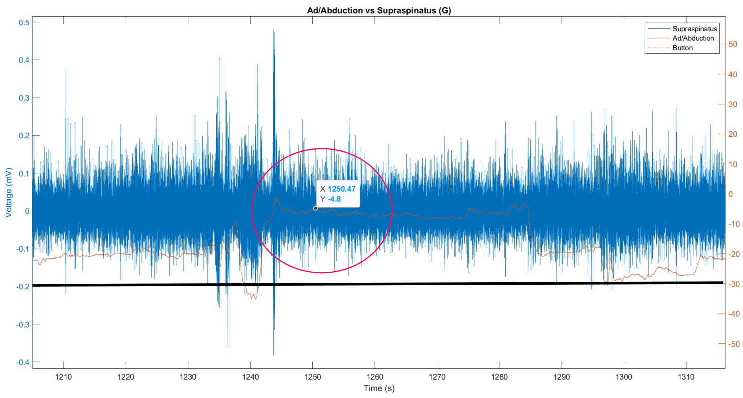


Figure 2.3v.2: Muscle activity supraspinatus with posture two encircled. Figure 2.3w.2: Posture two with reaching arm

3



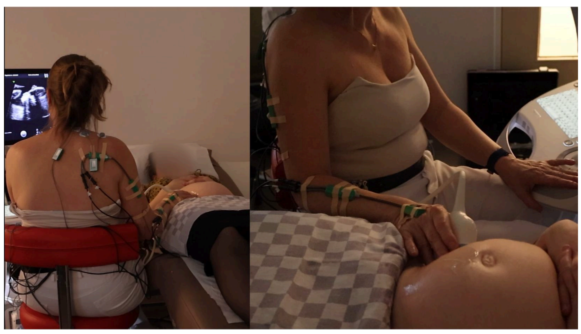


Figure 2.3v.3: Muscle activity supraspinatus with posture three encircled Figure 2.3w.3: Posture three with arm closeby

Trapezius
The activity of the trapezius did not change in any of the three postures depicted in Figure 2.3w.1-3. This may indicate that the trapezius is not used in all three postures. The muscle’s activity is depicted in Figure 2.3x.1-3.

Flexor
As explained before, the Flexor results are found in Appendix G.

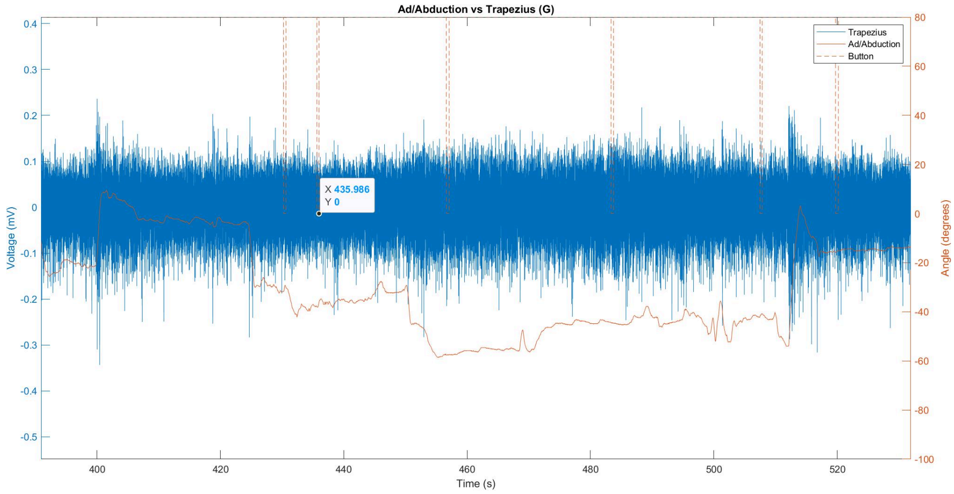


Figure 2.3x.1: Muscle activity of trapezius plotted against ad/abduction in posture 1

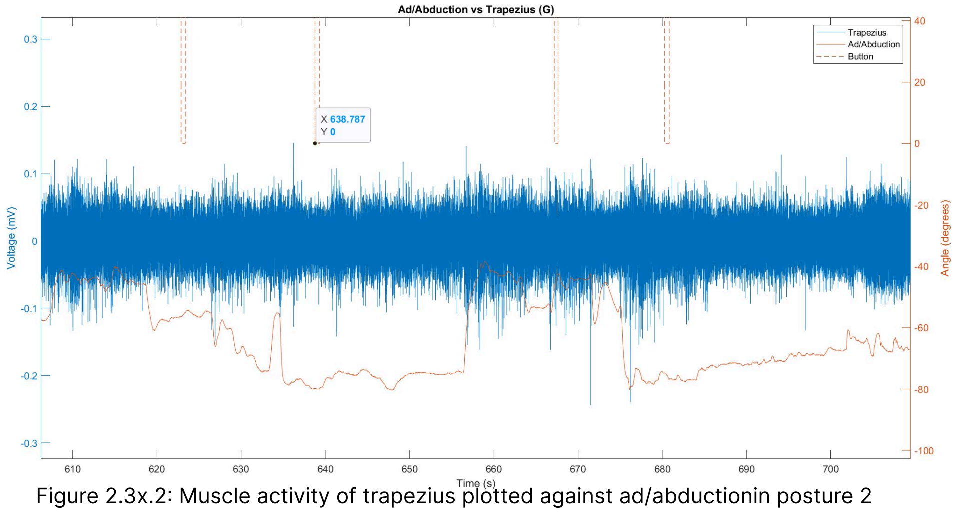


Figure 2.3x.2: Muscle activity of trapezius plotted against ad/abductionin posture 2

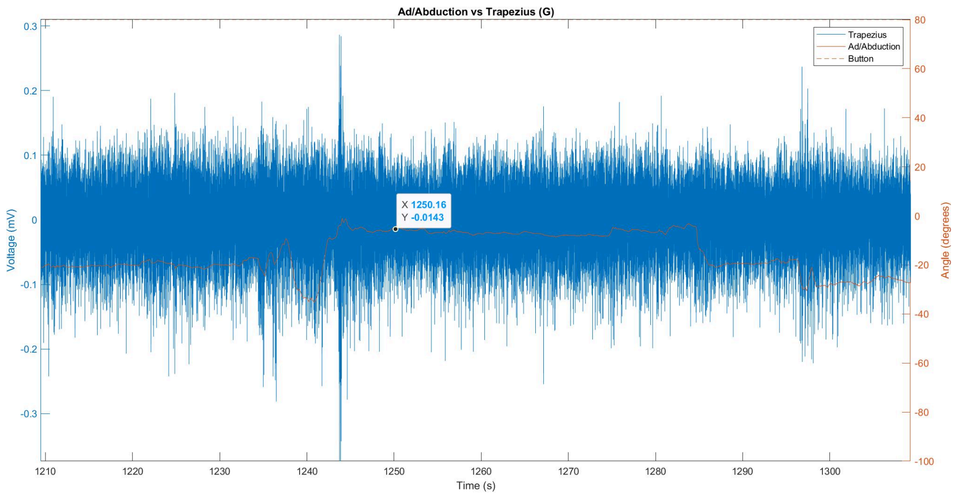


Figure 2.3x.3: Muscle activity of trapezius plotted against ad/abduction in posture 3

Pain moments gynaecology department

Due to the thinking out loud method, moments were recorded when the sonographer mentioned pain.

Twelve moments (A–L) were noted during the test, outside of the 43 posture changes (see Appendix H). In three of these moments, the participant reported experiencing pain. Images of the postures are seen in Figure 2.3y.1-3.

At moment **A**, the participant mentioned feeling pain in her upper arm, scoring it 3/10, and in her right scapula, scoring it 2/10. The participant said this was because she could not lean on the patient. The graph showing muscle activity indicates active supraspinatus in the minutes before, which could lead to shoulder muscle strain.

At moment **C**, the participant mentioned feeling her shoulder blades and biceps again. She emphasised her shoulder blades. Again, the supraspinatus was very active in the minutes before.

At the moment, the participant mentioned feeling her lower arm due to pushing with her finger. Her wrist was also not in a neutral position. The data shows that the flexor was very active due to the angle and force needed to maintain this position.

Figure 2.3y.1: Posture A with floating elbow circled

Figure 2.3y.2: Posture C

Figure 2.3y.3: Posture I

After conducting the test, the participant pointed out the area where she felt irritation, pointing at the trapezius and the origin of the supraspinatus at the shoulder blade. This is depicted in Figure 2.3z. On the bottom, an anatomical image of the shoulder area is provided for reference.

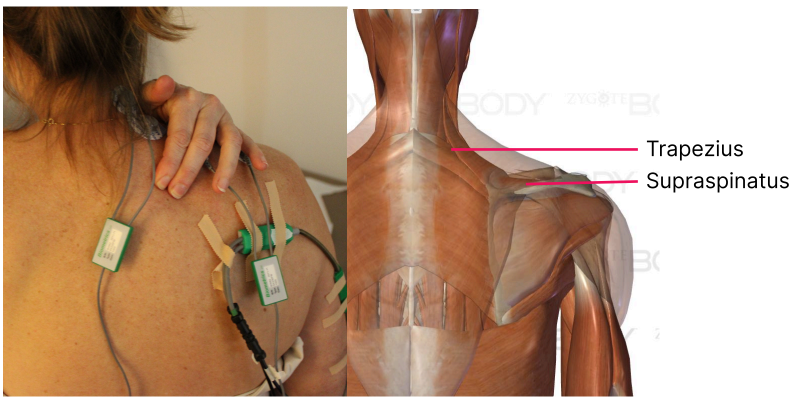


Figure 2.3z: Left: Picture of participants pain area. Right: Anatomy of body showing supraspinatus and trapezius (Zygote, n.d.).

2.3.5 Discussion and Conclusion

This study compared muscle activity and posture during ultrasound procedures in the paediatric cardiology and gynaecology departments. Although the tests were done in different settings with different postures of the patient (LLD and supine in cardiology, only supine in gynaecology), similar observations were found. The similarities appeared in shoulder abduction, supraspinatus activation, and flexor strain.

Abduction
Abduction over 30 degrees is a known risk factor for WRMD. In both departments, the arm was frequently abducted beyond this threshold. In the paediatric cardiology test, this happened in both the LLD and supine positions. The supine position showed more abduction, likely due to less elbow support, forcing the participant to hold the arm up.

In the gynaecology department, abduction was also common, especially in the second posture, where the arm reached up to 80 degrees due to reaching. The first posture in gynaecology showed just over 30 degrees of abduction, while the third posture involved almost no abduction, or even adduction, due to torso rotation and performing the ultrasound close to the body.

Supraspinatus Activity
In both tests, supraspinatus activity was closely linked to abduction and arm support. In paediatric cardiology, the muscle was active consistently, especially when the arm was floating or changing positions. The supine posture, where the arm had to be held up without support, caused higher muscle activation. This was most notable in the second posture, where the arm was abducted and flexed for two minutes.

In the gynaecology test, the supraspinatus also showed higher activity when the elbow was not supported. However, in the second posture, even though abduction was higher, the arm could rest on the patient, leading to less muscle activity. In the third posture, where the arm was close to the torso, supraspinatus activation was very low. This shows that support plays a key role in supraspinatus strain even more than the actual abduction angle

Trapezius and Flexor Activity
The trapezius activity was stable and relatively low in both departments. At the paediatric department, there were slight peaks during position changes, but overall it remained steady. In the gynaecology department, there was no clear change between postures, suggesting limited use of the trapezius during these procedures.
The flexor digitorum profundus showed continuous activity in both settings. In paediatric cardiology, flexion increased in the third and fourth postures, with higher EMG activity in the LLD position. In gynaecology, activity was stable in the first and second postures, but spiked in the third posture. This increase was probably caused by the arm being close to the torso and the wrist being flexed. This required more force from the lower arm than from the shoulders.

Pain Moments
In both tests, discomfort was reported in areas connected to high muscle activity. In cardiology, pain was felt in the thenar area, starting earlier and stronger in the supine position (up to 5/10). Cramping was also mentioned after longer periods of force application.

At the gynaecology department, three pain moments were marked. Pain in the upper arm and scapula (3/10 and 2/10) was linked to a lack of arm support and high supraspinatus use. Another moment showed lower arm pain when pushing with a flexed wrist, linked to high flexor activity. After the test, the participant reported irritation in the trapezius and the origin of the supraspinatus.

Conclusion
Across both departments, high arm abduction, poor arm support, and non-neutral wrist positions caused increased strain, especially in the supraspinatus. While the tasks and body positions varied, similar muscle responses and pain complaints appeared. These findings highlight the need for more support during ultrasound procedures to reduce the risk of muscle fatigue and WRMDs.

2.3.8 Limitations

There are several limitations to this test that should be considered when interpreting the results. First, while the supraspinatus was measured for shoulder abduction, other muscles like the deltoid and serratus anterior also play an important role in this movement and were not included in the EMG setup. Adding these could give a more complete picture of shoulder involvement. Also, the placement of the EMG stickers may have varied slightly between participants, which can affect the accuracy and consistency of the readings. Similarly, aligning the goniometer correctly was challenging, and in some cases, it may have shifted or come loose during the test, affecting the angle measurements.

Another limitation is the battery interruption that occurred during the paediatric cardiology test, which caused an unplanned waiting period and possibly affected the natural workflow of the participant. Also, knowing that the test is being done for analysis and not in a real clinical setting might cause the participant to be more relaxed or cautious, possibly changing muscle effort compared to real patient care.

In the gynaecology test, only three postures were analysed, even though 43 posture changes were marked, meaning only part of the data was studied in detail.

Lastly, ulnar and radial deviation were not measured in the paediatric cardiology test due to something going wrong, which could have given more insight into wrist positioning and possible muscle strain in that area.

Finally, it should be noted that the measurement of ulnar and radial deviation was not included in the results from the paediatric department. It is evident that an issue has arisen. The data potentially could have provided further insights into the wrist.

2.4 Conclusion Exploration Context

Once all the necessary information had been collected, the answers to the first two research questions could be found.

What are the key risk factors contributing to WRMDs among sonographers in paediatric cardiology and gynaecology departments?
The key risk factor is the abduction of the shoulder, which exceeds the limit of 30 degrees almost 50% of the time in both departments.

Additionally, the force applied to corpulent patients or in certain positions can result in hand pain due to gripping. Moreover, in these occurrences, the force that is delivered by the shoulder grows. This increases the shoulder tension on top of the part caused by just abduction.

Lastly, the sonographer's posture should be as neutral as possible, with the back straight and the arm close to the torso. However, this is not always possible due to the type of movements and the setup required for ultrasound performance.

What are the key differences and similarities in procedures and ergonomic challenges faced by sonographers in the paediatric and gynaecology departments?
The key difference between the paediatric and gynaecology departments is the type and frequency of movements required to perform an ultrasound. In the paediatric department, the probe is placed in a static and predictable position. In the gynaecology department, the entire lower abdomen is covered and the position often changes.

Another difference is the position of the patient. For younger children, the ultrasound is performed with the patient in a supine position. From the age of approximately eight years, the first part is performed in the de LLD position and the second part in the supine position. In gynaecology, the patient is in the supine position. However, they sometimes lie on their side if they feel light-headed or if the baby needs to be in a different position. Ironically, these differences make for a similarity in the sense that both contexts require flexibility.

Next is the knowledge of how to perform ultrasounds ergonomically. In both departments, sonographers teach each other ultrasound techniques. Whether or not this includes scanning ergonomically depends on the knowledge that was passed on to the senior sonographer.

Key insights
In order to give a summary of all the problems found in all the departments, an overview was made to present the findings in a simple way and to make them more understandable with the drawings. The overview is shown in Figure 2.4a. The figure shows on the top left the two factors contributing to the WRMDs in the shoulder. The other drawings are challenges that contribute to this.

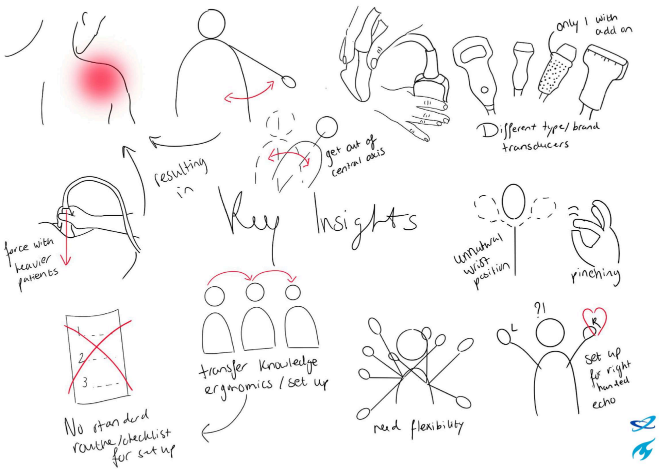


Figure 2.4a: Key insights

3 Problem definition

This chapter explores the underlying causes of work-related musculoskeletal disorders among sonographers at RdGG. Through thematic content analysis, observations and stakeholder input were synthesised to identify key factors contributing to physical strain during ultrasound procedures. The findings are grouped into core problem clusters, mapped within a Circle of Influence to distinguish what can be addressed through design. This analysis led to the formulation of a clear problem statement, which led to the development of the first part of an ergonomic support system. The chapter concludes with a personal reflection on the identified challenges and the potential impact of the proposed design solution.

3.1 Getting to the Core: finding key factors contributing to WRMDs

Intro
To determine the core problem that causes WRMDs at RdGG a thematic analysis was done to see underlying relationships and to create a focus area of the design.

3.1.1 Method

A thematic content analysis (TCA) was conducted inspired by Braun and Clarke's six-phase framework (2006). Although formal coding was not applied, a system of color-coding was used to organize the data. The analysis involved familiarisation with the data from observational notes and founding from the EMG test, followed by the identification and refinement of themes based on recurring patterns

Procedure
Three steps were taken to get to the core key factors. Each step will be briefly addressed to highlight the analysis of the process.

Step one: Problem group
The findings of all the separate studies presented in Chapter 2 were put into a matrix. They are divided into three categories: physical(blue), environmental(green) and organisational (pink). The category physical describes the problems of the sonographers themselves. The category environmental describes factors outside the sonographer that influence the WRMSDs. The category organisational describes procedures and education in sonography.

Relations are illustrated by lines showing differences, similarities and cause-effect. The darker colour represents the paediatric department, and the lighter colour represents the gynaecology department. Figure 3.1a shows this matrix and the complexity of this problem.

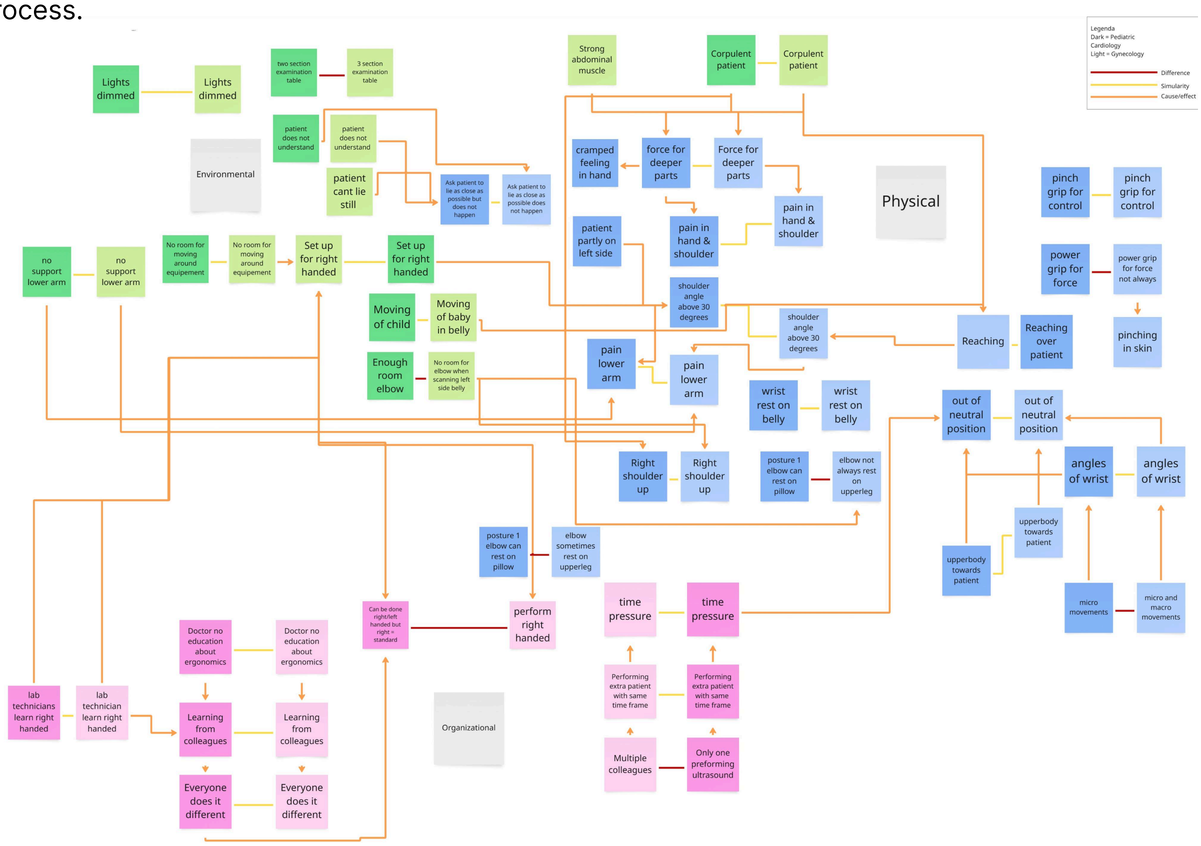


Figure 3.1a: Impression of Problem Matrix. On the left top in green: Environmental factors. On the bottom left in purple: Organizational factors. On the right in blue: Physical factors.

Step two: core problem
The problems and observations were clustered to find an underlying meaning of the relations, as shown in Appendix I.
Nine clusters were made based on the meaning behind the findings. Three subjects appear double: the setup is for right-handed sonography, elbow resting and reaching. These topics are extremely relevant for WRMDs caused by sonography and belong in multiple core problems.

Step Three: The Circle of Influence
The circle of influence is a method to focus on the things you can control and influence (Holmer, 2022). This creates the opportunity to decide what part is out of scope for this project after the observations.

The middle circle describes what is possible to directly control through actions. The second circle describes what we can do something about, but possibly influence the outcome. Lastly, the outer circle describes what we have no control over.

3.1.2 Results TCA

The result consists of two parts: the explanation of the core problem clusters and the clusters mapped on the Circle of Influence. The core problems are explained to show the meaning of the problem, and the Circle of Influence shows which problems will be solved in this project and which will be part of a future vision.

Core problem clusters explanation

Patient collaboration affects ergonomic posture. This cluster highlights how patient cooperation can support ergonomic sonography. When patients move closer to the sonographer, it reduces reaching and strain. However, communication barriers or cognitive limitations may hinder understanding. In paediatrics, anxiety or restlessness makes stillness difficult, while in gynaecology, fetal movement is unpredictable. In both cases, a lack of patient cooperation can force sonographers into non-ergonomic positions to obtain a clear image.

Patient diversity affects ergonomic posture. This cluster explains how patient diversity impacts sonographer posture. Overweight patients require more reaching and force to obtain clear images, leading to strain in the hands, arms, and shoulders. In paediatric cardiology, the firmness of the abdominal muscles in children also demands increased pressure due to the heart's depth that needs to be reached. These factors contribute to WRMSDs.

The room setup hinders ergonomic working. Most hospital setups are designed for right-handed sonography, reinforcing right-handed teaching and limiting flexibility. This setup often forces sonographers to work with raised arms, extended reaches, and no lower-arm support, which contributes to poor ergonomics. While setup changes were discussed in the co-creation session, they are considered a long-term vision.

Trade-off between ergonomic grip and image quality. This cluster highlights the challenge of balancing ergonomic hand posture with sonogram quality. The pinch-grip offers precision but increases strain, while the power-grip allows more force but less control. Grips exceeding 0.9 kg (pinch) or 5.5 kg (power) are linked to higher WRMSD risk (Zangiabadi et al., 2024). Although the power-grip is theoretically more ergonomic, it's not always practical in sonography due to less precision.

Education and knowledge transfer impact ergonomics
This cluster highlights how ergonomics in sonography is shaped by informal, colleague-based training for doctors. What one learns depends on the teacher's habits, including whether both-hand use is encouraged. The cycle of right-handed teaching continues, and switching to left-handed techniques later requires significant effort due to ingrained habits.

Freedom of movement affects ergonomic posture. Sonographers need freedom of movement to access the area of interest. Paediatrics involves more micro-movements, while gynaecology requires both micro- and macro-movements. Limited space often leads to raised shoulders and awkward arm positions. In paediatrics, elbow support varies by posture of the patient; in gynaecology, resting the elbow on the patient's thigh is sometimes possible but limited by movement range. Scanning the left abdomen often forces the elbow into an unnatural, cramped position.

Time pressure compromises ergonomic practice.
Under time pressure, sonographers often prioritise patient care over their own ergonomics. When schedules are overloaded, maintaining neutral wrist, shoulder, and upper body posture is frequently neglected. Reaching increases to quickly access the area of interest, especially when dealing with restless children. This leads to greater physical strain.

Coping mechanism
This cluster describes how the department currently copes with trying to do the sonography as ergonomic as possible. This does not include the adjustable equipment. It is interesting to see if the pillow used in the paediatric department can also be a solution at the gynaecology department.

Influence design
This category was created to place findings that were not problems resulting in WRMDs, but are factors that could influence future designs. These factors include similarities and differences between departments and are, therefore interesting to keep in mind. For example, the differences in the type of examination table.

Circle of influence

All the clusters have been placed into the Circle of influence shown in Figure 3.1b to determine the focus of this project.

Circle of control

The circle describes three core problems: the freedom of movement, the coping mechanism and the collaboration with the patient. These three can be influenced by the design of a tool.

Circle of influence

The circle describes two core problems: the setup of the room and diversity in hand grip. These are places of influence because they are both linked to organisational influences that concern education, as well as how things are done at the hospital. This requires a big step in changing behaviour and also the available space in the hospital. This can be influenced by the design, but is partly out of scope.

Circle of concern

The circle describes three core problems: time pressure, education & knowledge transfer, and patient diversity. Time pressure is a problem that requires a major change in the organisation and is sometimes unavoidable. As mentioned in the relationships between core problems, making the setup so that there is no option to work non-ergonomically can indirectly influence this problem.

Education and knowledge transfer is a big problem with many stakeholders outside this project, think of the schools, but also all the other hospitals where AIOS are trained. Any findings from this project can lead to recommendations, but changing this is beyond the scope of this project. Finally, the diversity of patients, especially obesity, is a big contributor to the problem of having to use a lot of force to get a good ultrasound. Although rejecting these patients or curing obesity would solve the problem, this is not realistic. However, creating a tool to help manage these force problems could have an impact on reducing the force needed.

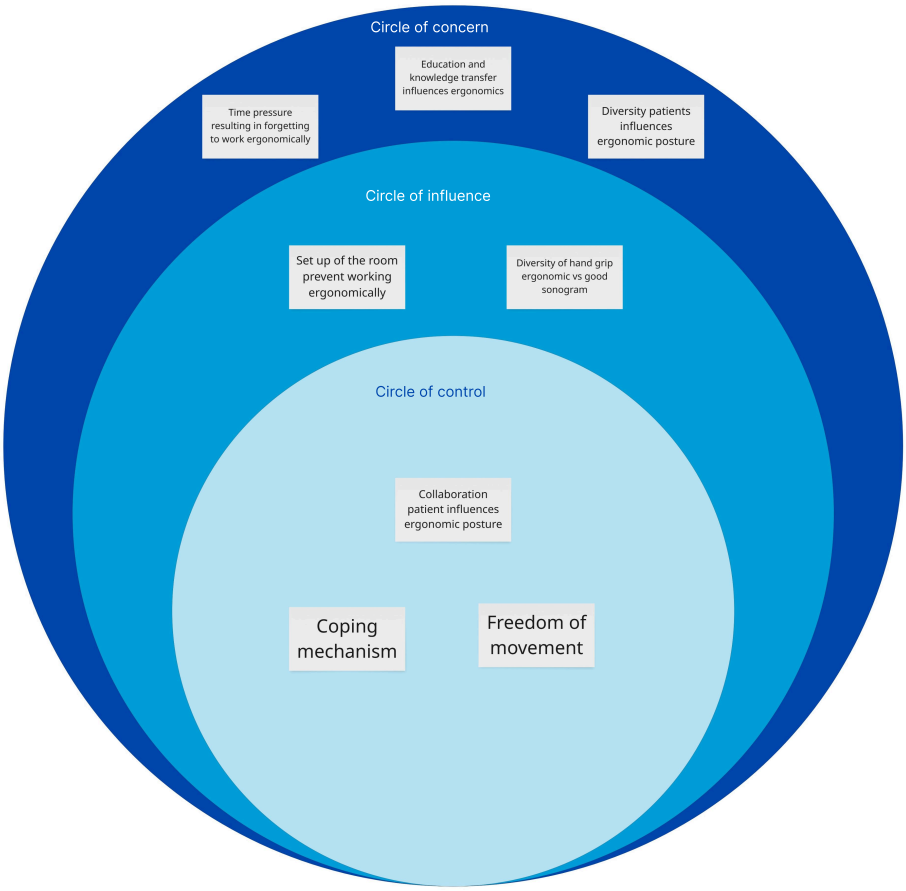


Figure 3.1b: Circle of influence

3.2 Problem Statement

Based on the Circle of Influence, a problem statement could be formed to give a more focused direction to this project.

Prevention is better than cure, and one preventive measure could be alternating between using the left and right hand during sonography. However, since this lies within the "circle of concern" rather than immediate control, it remains a long-term vision.

After consulting several experts, including H. Laurijsen, it became clear that, until such a future is realised, support is needed for the arm and shoulder, along with assistance in applying physical force.

Even if this vision becomes reality, the issue of applying force will persist. As Figure 3.2a shows, obesity in the Netherlands is on the rise. This, combined with children who have strong abdominal muscles and an increasing number of overweight patients, will only make the physical demands of sonography more challenging.

A way of tackling the force could be by using a robotic arm to take of the force application of the sonographer. Robots like this that still leave the craftmanship to the user but assisting them in force application is already found at the TU Delft, see Figure 3.2b, as this one used at KLM preventing shoulder complaints while sanding wind blades (Kuiper, 2024).

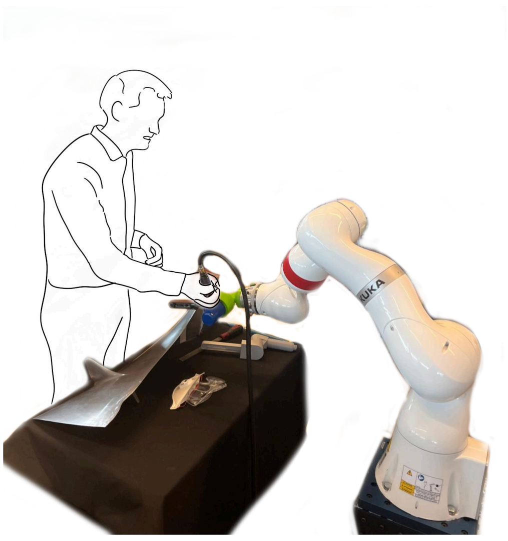


Figure 3.2b: Robot in use

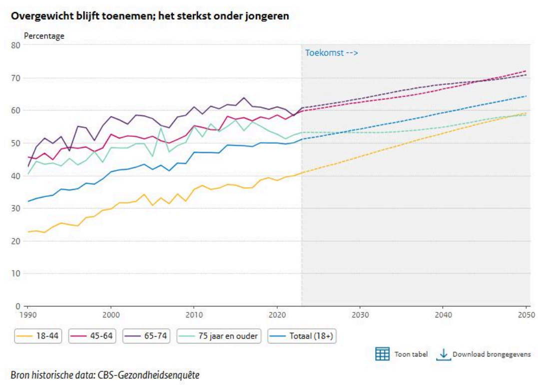


Figure 3.2a: Increase of obesity in the upcoming years (Centraal Bureau voor de Statistiek, 2025).

3.2.1 Problem Statement

Sonographers frequently perform procedures with their shoulder elevated above 30 degrees, the arm extended out of its natural resting position, and the elbow unsupported. This posture places continuous strain on the shoulder and upper arm muscles, leading to fatigue, discomfort, and a high risk of WRMDs. Existing solutions do not adequately address the need for both immediate ergonomic support and force assistance during scanning tasks.

This project will focus on developing the first part of a two-part system:

1. Remus: A short-term support device designed to stabilise the arm and shoulder during scanning, reducing muscular load caused by elevated and unsupported arm positions.
2. Romulus: A long-term assistive device capable of applying controlled, consistent force on the ultrasound probe, reducing the sustained effort required by the operator throughout lengthy procedures.

Both parts of the system are needed to support the sonographer. Romulus is only called long-term because if the arm support is not needed anymore due to dual hand scanning, this design is still relevant.

It is possible that in the future, both support and force will be integrated into one product.

3.2.2 Interpretation of the Problem Statement

In conclusion, we see a profession that demands far more from the human body than is sustainable. The ergonomic challenges in sonography are not solely the result of individual posture but are driven by systemic factors embedded in training, equipment, and clinical workflow. The problem statement highlights how frequent elevation and extension of the arm contribute significantly to WRMDs.

Focusing on short-term support through Remus is a necessary and realistic first step. While future technological innovations may eventually reduce or restructure the physical demands of sonography, these are long-term solutions requiring time and investment. In contrast, immediate ergonomic support offers practical relief and can help initiate a cultural shift toward greater awareness and prevention of WRMDs.

The proposed two-part system acknowledges the complexity of the issue, addressing both immediate and long-term needs. This layered approach reflects the diverse physical demands across sonography departments and supports a more sustainable practice for professionals in the field.

4 Finding opportunities

This chapter explores various design possibilities that help to prevent WRMDs due to ultrasound practices, resulting in two concepts that are prototyped. Through testing with sixteen different healthcare professionals, numerous design requirements were identified. In addition, a concept was chosen. The chapter concludes with a list of requirements that forms the basis for the final design.

4.1 Design process

Different activities have been conducted to contribute to the ideation and finding opportunities. To give an idea of what type of activities contributed, Figure 4.1a shows an overview of the different activities with the findings. All the activities with explanations can be found in Appendix J.

Brainstorm fellow student

- **Hanging constructions** give opportunities but can't come from ceiling due to regulations hospital.
- **Change setup of ultrasound room** to change posture of sonographer.

Co-creation hospital

- Paediatric department has more **micro-movements** compared to gynaecology with **micro and macro movements**.
- Changing setup would need involvement of industry and is therefore more a **future vision**.
- Product should provide the user with a **feeling of control.**

Provotyping

- Ensure **blood circulation**.
- Accommodate **all body types**.
- Make sure the product can hold **pulling** of the patient.
- The design should not create a **feeling of restriction.**
- All contact points should be **soft and free of sharp** edges.
- The product **should not block line of sight** or disrupt communication.
- The materials should be **easy to clean**.
- The product **should not hinder moving** around in the ultrasound room.

Brainstorm fellow student 2

- The product should be **as small as possible** but still should give adequate support for p20-p80.

Figure 4.1a: Overview activities in the design process.

4.2 Two concepts: Leaning vs Hanging support

Throughout all the brainstorms and co-creation sessions two products were designed which mechanism had to be tested in the context: the leaning and hanging support. In this section both ideas and prototypes will be explained.

4.2.1 Leaning support

The leaning support assists the supraspinatus and deltoid muscles when the arm is abducted. It does this by providing an upward force to assist with lifting the arm. The product attaches to the bed rail (see Figure 4.2a) to provide stability. The user places their arm over the product, positioning it between their torso and upper arm. They can then lean onto the product while the ultrasound is performed. When the probe needs to be in a more proximal position, the support can be turned to create space. The product's height can be adjusted to accommodate different body types.

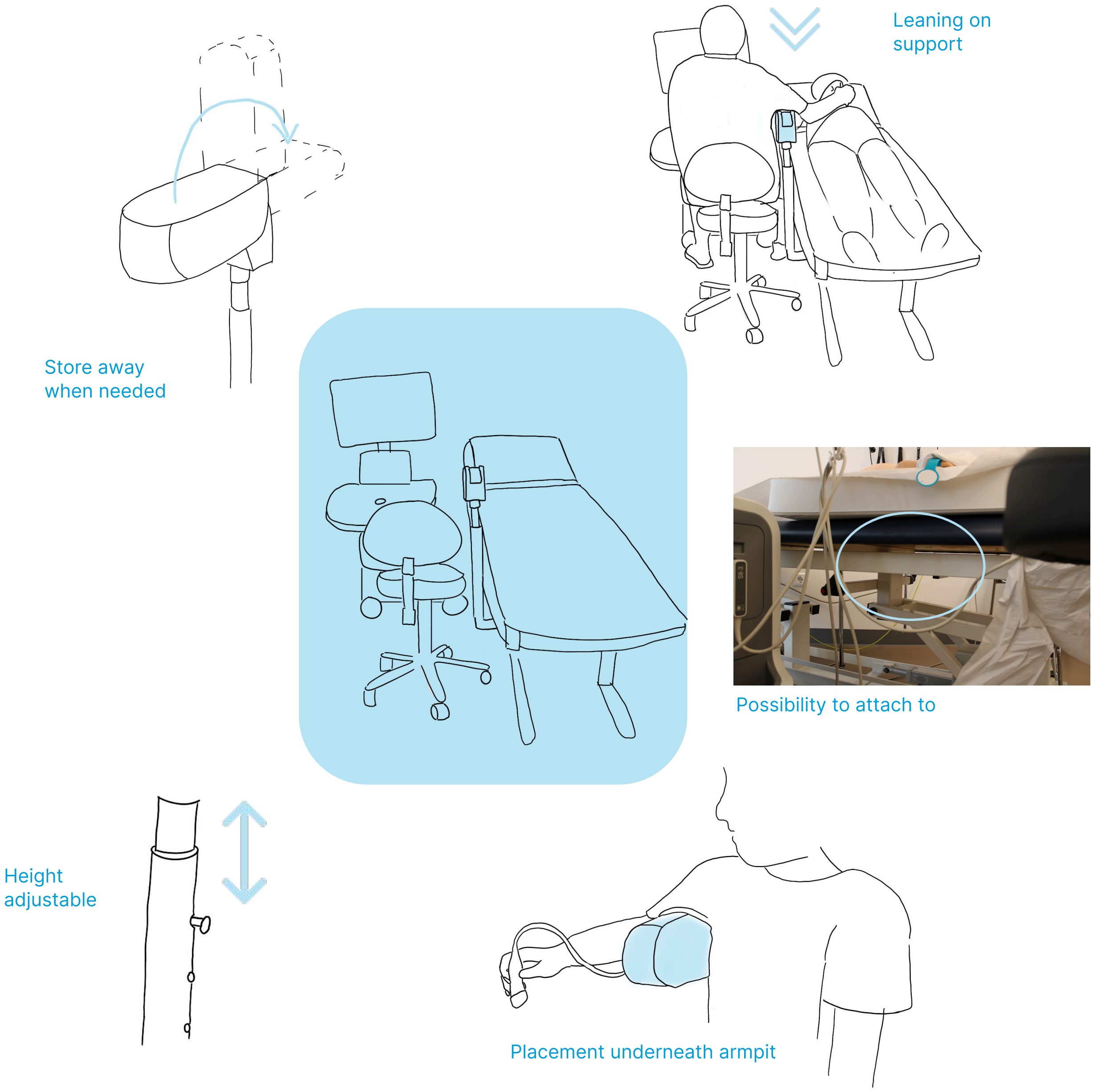


Figure 4.2a: Leaning support drawing and functionalities

Leaning support prototype
A prototype was built (see Figure 4.2b) to test the working mechanism of the leaning support. As testing took place in different hospitals, set-up time had to be minimised so as not to occupy the room for too long. Instead of mounting it onto the examination table, a standing variant was made. Also, it was not known which rooms were available or what type of examination tables were used, so a standing variant was the safest option. The rest of the design remained the same, enabling the prototype to be set to the correct height and moved away when not in use.

The foot was made of wood with a steel holder in the middle. The base consists of two PVC tubes connected by a bolt. The upper part is connected with a 3D-printed holder. The turning base and the leaning beam are also made of wood. A leather-covered cushion was placed on top of the leaning beam to make it soft and easy to clean.

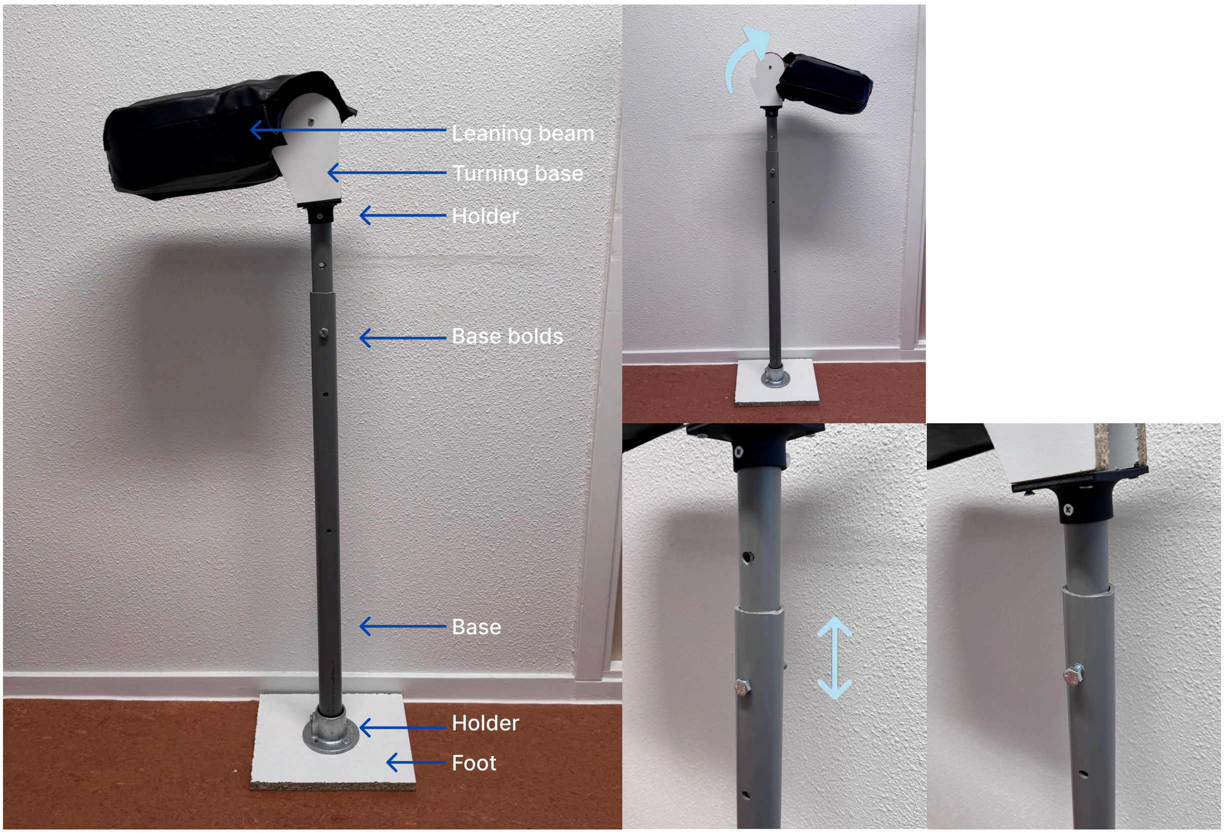


Figure 4.2b: Prototype of leaning support and it's functionalities.

4.2.2 Hanging support

The hanging support assists the supraspinatus and deltoid muscles by helping to lift the weight of the arm. The support is attached to the base of the chair. The arm is placed inside a sling attached to a spring system. This spring system has several levels of resistance to accommodate different body types and arm weights. Thanks to the spring system, the arm can make all the same movements relative to a static sling. Figure 4.2c shows a drawing of the product and its various functions.

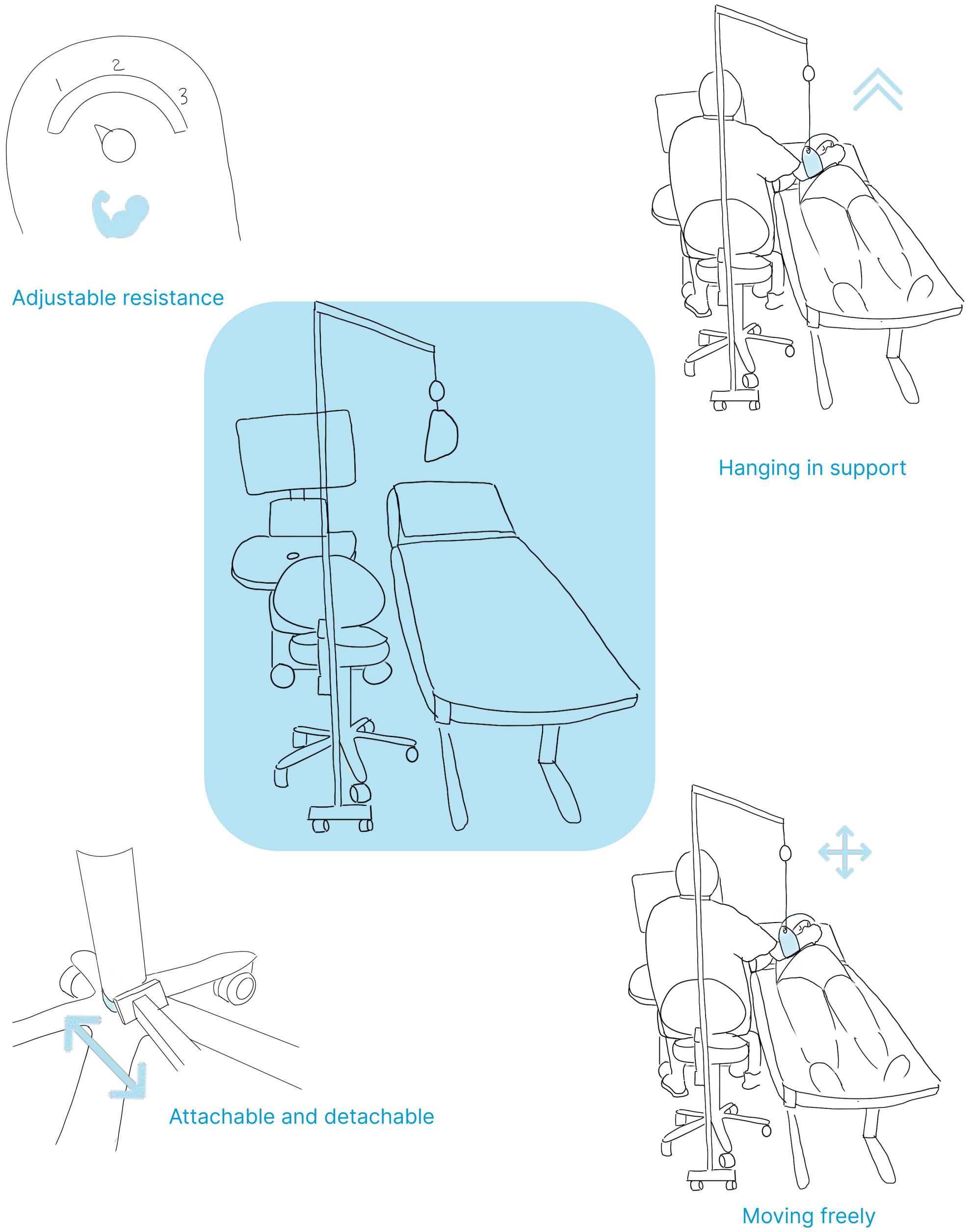


Figure 4.2c: Hanging support drawing and its functions.

Hanging support prototype

A prototype was built (see Figure 4.2d) to test the mechanism of the hanging support. A wooden model was made that could be attached to and detached from the stool. There is a pivot point at the end of the arm where it connects with the base. This allows the arm to be moved above the examination table.

The spring mechanism is a store-bought mechanism used in the car industry. The spring inside can be set to different strengths to alter the resistance. The sling is made of leather to resemble a fabric that can easily be cleaned.

Figure 4.2d: Hanging support prototype.

4.3 Expert Testing

The aim of this test was to evaluate two support instruments, the leaning support and the hanging support, and determine which is the most comfortable and suitable for use in the paediatric and gynaecology departments.

4.3.1 Method

This paragraph describes a brief overview of the setup of the test. The entire test plan can be found in Appendix K.

Participants

A total of fourteen healthcare professionals participated in the test, ranging in age from 28 to 65 years old. These included five gynaecologists, seven paediatric department staff (including five laboratory technicians and two doctors) and two HSE coordinators. It was important that both departments were represented equally. The HSE coordinators are expert on ergonomics and give an insight if the instruments could be used in the hospital.

The participants' experience of performing ultrasounds ranged from 0 years (the two HSE coordinators) to 30 years. It is important to have a wide spread of experience levels. This allows us to test if the product is suitable for beginners as well as experienced sonographers. The tests were performed at Reinier de Graaf Hospital, Erasmus Medical Centre and Leiden University Medical Centre. The ratio of males to females was three to eleven, reflecting the gender distribution within the medical field in Europe (Pedersen et al., 2021). The participants were recruited through hospital and personal connections.

Materials and Procedure

Figure 4.3b shows both prototypes in the testing context at the hospital. In the paediatric department a resuscitation doll was used to represent the baby and children patients. At the gynaecology department, a pillow with a piece of leather stretched across was used to represent the mothers belly.

Participant	Gender (f/m)	Age	Length (cm)	Pain with sonogram (y/n)	Work experience (years)	Main hand (L/R)	Remarks
1	f	28	168	y	0	R	Test ergonomics
2	f	29	167	y	0	R	Test ergonomics
3	m	45	186	n	8	R	
4	f	51	160	y	19	R	
5	m	40	188	y	4	R	
6	f	49	158	y	24	R	
7	f	50	172	n	26	R	
8	f	50	167	y	24	R	
9	m	65	182	n	30	R	
10	f	42	171	y	16	R	
11	f	32	175	y	1,5	R	
12	f	47	178	y	22	R	
13	f	25	168	y	4	R	
14	f	43	164	y	18	R	

Figure 4.3a: overview of demographics

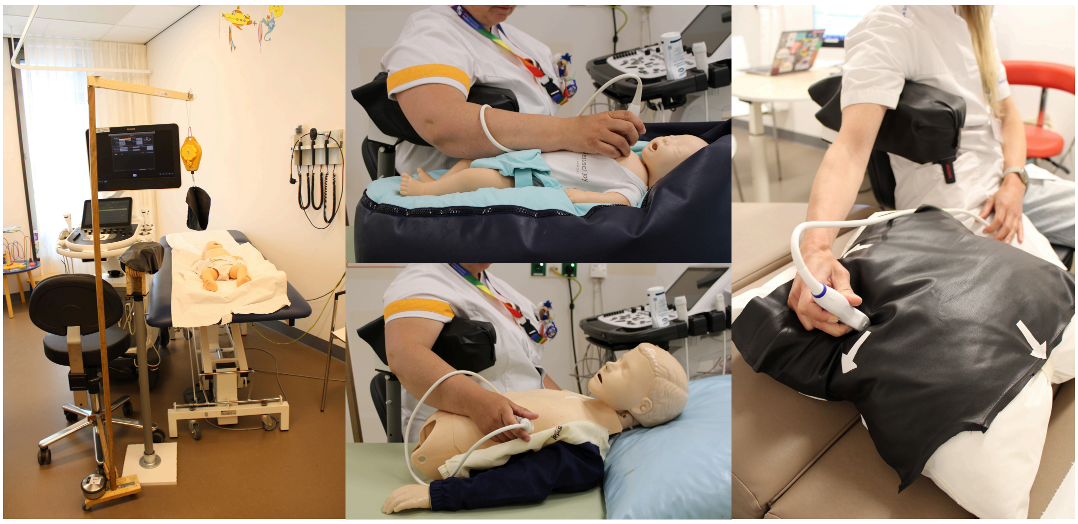


Figure 4.3b: prototypes in context and the different patient

In the first part of the test the participants were informed about the focus of this graduation project and the aim of the test. Next the participants answered questions about their demographics to get an insight in their background.
In the second part of the test, the two products were presented using two illustrated posters. Participants tested both products for a few minutes to try out the movements they use in their procedure. During the procedure participants were asked to think-aloud and notes were taken in the excel sheet shown in Appendix K. At the same time pictures were taken.

After testing the first prototype, they were asked seven questions about the following topics:

- Comfort: *What was the comfort during use?*
- Fit: *Does the prototype fit your body well?*
- Freedom of movement: *Where you able to make all movement required to perform the ultrasound?*
- Pressure points: *Did you feel any pressure points, pinch point or irritation during use?*
- Material: *How did the material feel on your body during the use?*
- All-day use: *Could you use the product the entire day? What are the barriers?*
- Support: *Did the product provide enough support?*

They had to give each the topic a score between 1 (not at all) and 5 (absolutely) and validate their answer.

Lastly, participants were asked to complete a comfort map (see Appendix K) to visualise where they felt comfortable and the locations of any discomfort. A comfort map enables participants to indicate the location of discomfort more precisely than they could by verbal description, and to compare the discomfort experienced in different body parts, making it easier to identify which areas need to be focused on in the design.

The same procedure was followed for the second prototype. To make sure all results can be compared, all participants first tested the leaning support and then tested the hanging support. At the paediatric department, all participants started the procedure with the baby. After that, they tested for a scan with the child on their side and ended with the child on their back, as to mimic the real-life procedure.

To conclude the test, participants were asked to choose a favourite product and justify their choice.

The full test procedure is described in Appendix K.

Ethics
All participants were asked to sign an informed consent including the following statement to give their preference about them being in pictures:
I give permission for using photos of my participation:
(select what applies for you)

- in which I am recognisable in publications and presentations about the project.
- in which I am not recognisable in publications and presentations about the project.
- for data analysis only and not for publications and presentations about the project.

The document structure of the informed consent form can be found in Appendix A.

Next to, this all demographic information will noted anonymously with only the participant ID.

Analysis
An average will be calculated of the fourteen participants. The results of each product will be addressed by the seven topics mentioned in the Method section. The answers were clustered according to similarities.
Lastly, the results will be interpreted and a choice of concept will be made.

4.3.2 Results comparing the two prototypes

Figure 4.3c shows an overview of the average scores awarded by participants. The Leaning support scores better than the hanging support. Figure and 4.3d shows the average score from the comfort map. Also in this case has the hanging support an better over score in comfort.

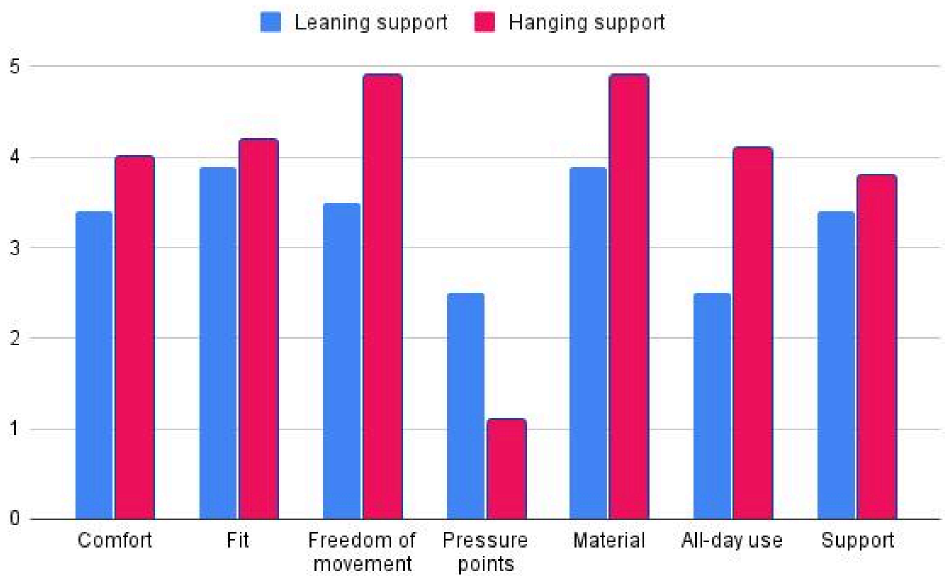


Figure 4.3c: Bar chart with average scores

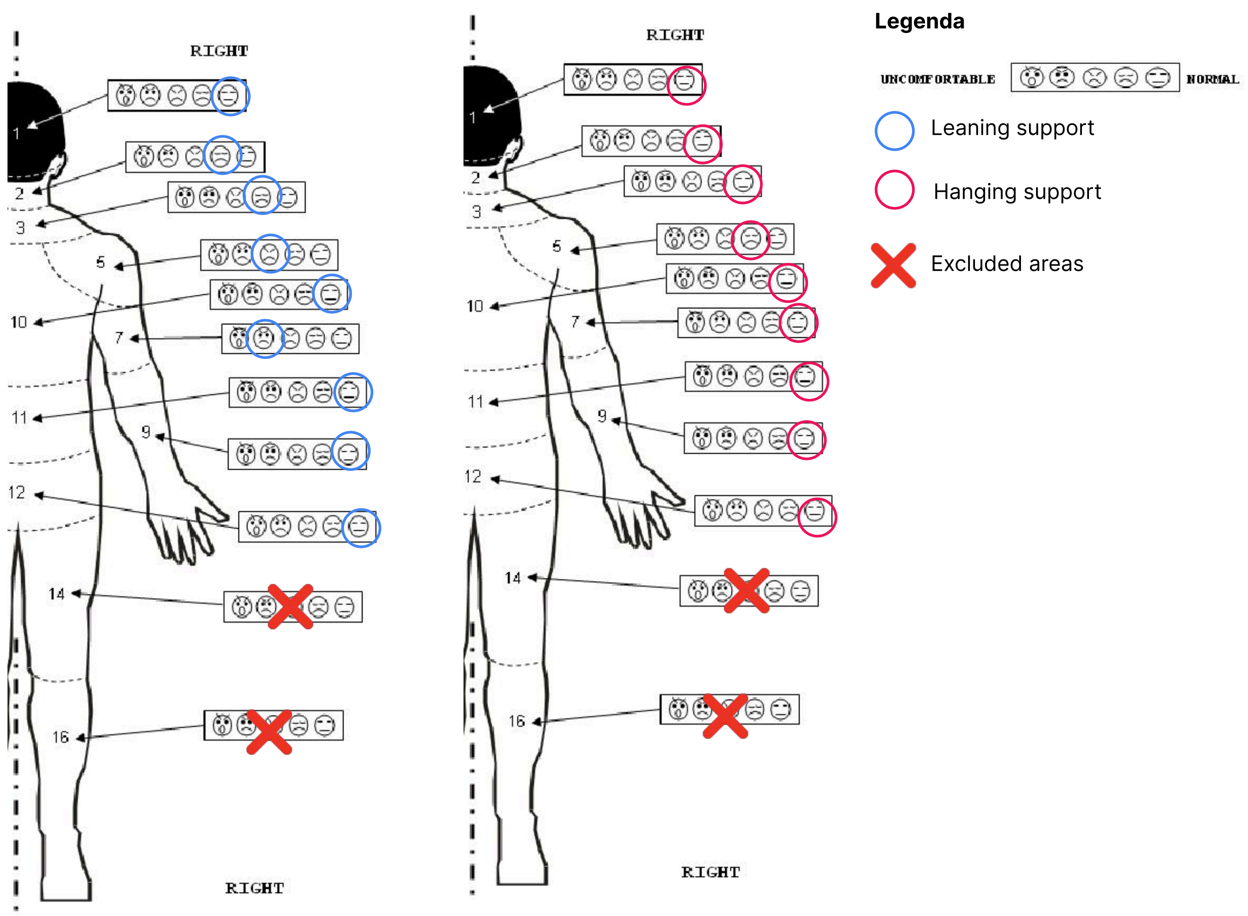


Figure 4.3d: Comfort map findings. Left: Leaning support, Right: hanging support.

4.3.3 Results Prototype 1: Leaning support

The findings of the seven questions mentioned in the method section will be discussed separately in this paragraph.

Comfort
The average comfort score was 3/5. Four participants mentioned pressure points in the armpit and upper arm area as shown in Figure 4.3e. While the products helped to relieve muscle tension, it took some time to get used to having something in the armpit.
Three participants appreciated the hanging/leaning feature, but there were concerns about restricting movement. In the gynaecology department, it was mentioned that so many movements were required that moving the support away was not an option and could even be annoying. The product acts as a reminder to maintain good posture as it creates a barrier for the upper body to prevent leaning, as is shown in Figure 4.3f.

Fitting
The average fit score was 4/5, with five participants saying it was a perfect fit. However, two found the product too wide. These results highlight the importance of adjustability, next to the need for more height adjustment options. A high degree of adjustability is crucial, but it takes time for the user to set accurately. One participant noted the potential danger of users not adjusting the height due to laziness, which can lead to other ergonomic problems. The support should extend above the patient's torso while still remaining in line with the user. In addition, the cushioning should extend towards the pivot point circled in light blue, as this feels like the sturdiest spot to place the arm.

Figure 4.3e: Place of pressure point

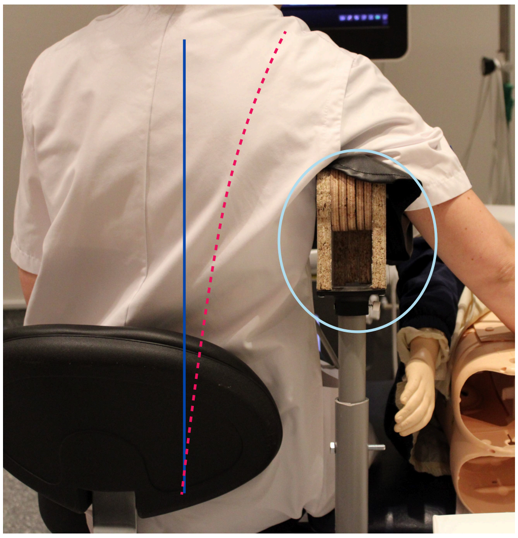


Figure 4.3f: Red line represent curve of the spine without the product. Blue line with the product.

Design Insights

- *Limit the number of action as it can be annoying.*
- *Have enough adjustability but make it easy to set to encourage people to set is correctly.*

Freedom of movement

Forty-three per cent of the participants experienced enough freedom of movement to perform the ultrasound. Almost all of these were from the paediatric department, which was expected, as fewer changes in movement are needed compared to other departments.

In the gynaecology department, the biggest restriction of movement was during scanning close to the user's body. Although the participants were aware they could move their arms away, it was found to be annoying because such movements occur repeatedly during the procedure.

In the paediatric department, the abdominal position (as shown in Figure 4.3g) was slightly restricted, but only two of the seven participants mentioned this. Additionally, due to babies being placed at the end of the examination table (as noted in Chapter 1), the product's positioning needs adjustment. By placing it on the chair instead of the table, it can move with the user, eliminating the need to reposition it between patients.

Pressure points

This was a difficult question to answer because the test only lasted a couple of minutes, so participants were asked to imagine whether pressure points could occur with longer use, even if they were not experiencing them at that moment. 36% mentioned pressure points in the upper arm, and 21% mentioned armpit irritation. This was mostly due to the fact that nothing is usually placed in the armpit in daily life because it is a sensitive area. There was a lot of concern that the arm could go numb over a longer period of time, which is the opposite of what we want to achieve.

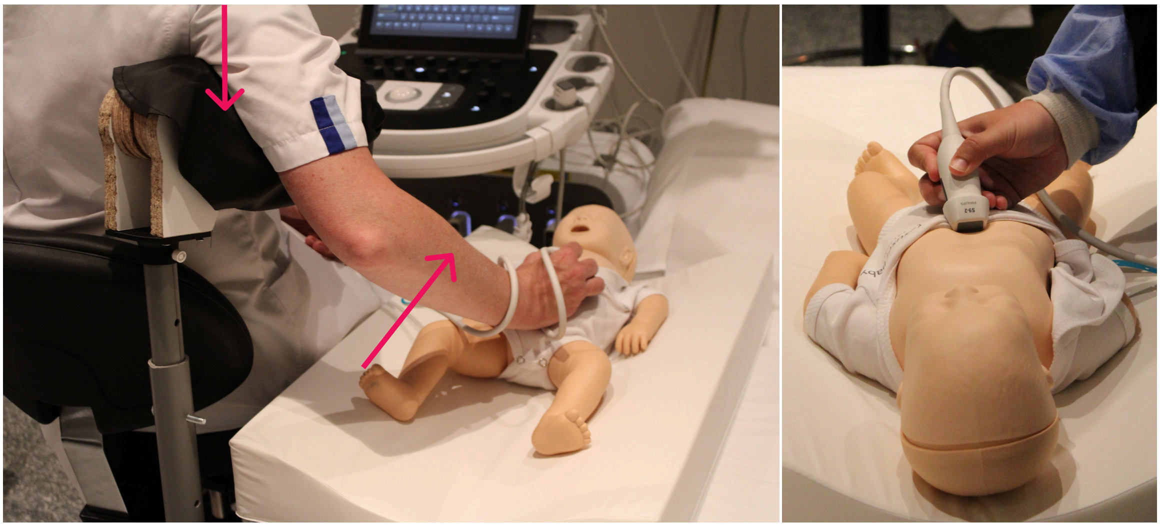


Figure 4.3g: abdominal position paediatric department. Arm needs to lower, as depicted by the arrow, but is restricted by product.

Design Insights

- *The product should have limit actions as this is found annoying.*
- *The product should be place on the chair to enlarge mobility.*
- *The arm should not limit bloodflow to prevent it from going numb.*

Material
In general, the material that was in contact with the body was perceived as being comfortable and soft. Two participants expressed concern that the leather material could become sticky, and therefore suggested that another fabric would be better as long as it is cleanable with water/ alcohol wipes.

Use entire day
This was a difficult question to answer because the test only took a couple of minutes, so participants were asked to imagine what the barriers to all-day usage would be. In theory, most people could use the product all day, but there were some limitations. Alternating between patients was suggested as a compromise. Limitations in freedom of movement and pressure points were cited as reasons not to use the product at all.

Support
Sixty-four per cent of participants indicated that the product provided the expected level of support. Three participants mentioned that they experienced the support, but noted limitations such as the absence of lower arm support. However, the barrier the product creates was seen as a positive way to encourage a more upright posture.

General notes
With years of experience, most users can place the probe blindly, which is convenient in the paediatric department when the patient is lying on their left side and you need to reach the lower part of the body. However, when the user is a beginner or the patient is a difficult case, the user sometimes needs to check the placement. Currently, the product obstructs this. It is also important to position the patient as close to the user as possible. The product should not prevent this.
As explained in Section 2.3, in the paediatric department, a pillow was used to create similar support for the patient. One participant mentioned that they had to lean much less on the patient. “This is more comfortable for me, but it also puts less pressure on the patient.”

Design Insights

- Fabric should be cleanable with alcoholic wipes.
- Vision of the user on the patient should not be obstructed.
- The patient should be able to lay as close to the user as possible and not be obstructed by the product.

4.3.4 Results Prototype 2: hanging support

Comfort
The average comfort score was 4/5. Three participants said that they could relax, with one describing it as "like relaxing in a hammock." However, three others noted that they had to get used to leaning fully into the product. One participant emphasized that, despite the comfort of hanging in the sling, the user should always remain able to assist if a baby starts moving. The freedom of movement also contributed to the overall comfort level, as it did not interfere with the procedure.

Fitting
The fit was nice and the shape of the sling provided good support. In the paediatric department, the preference was to place the sling over the elbow to provide more support. One participant reported: 'Having the sling around the elbow gave me a greater sense of control.' However, because the arm hangs more straight down when the patient is lying on their side, the sling tilts, resulting in less support (see Figure 4.3h). Only one participant mentioned this problem. Another contributing factor was that the spring base was not positioned correctly above the elbow, which limited the support. The ideal point of support would be above the elbow, as shown in Figure 4.3i, therefore the product alignment should be straightforward to prevent it being used incorrectly.
Good product alignment also prevents the upper body from bending too much over the patient.

Another important point is that the arms can be covered in gel, which can result in the sling getting dirty. Therefore, the sling should be easy to clean.

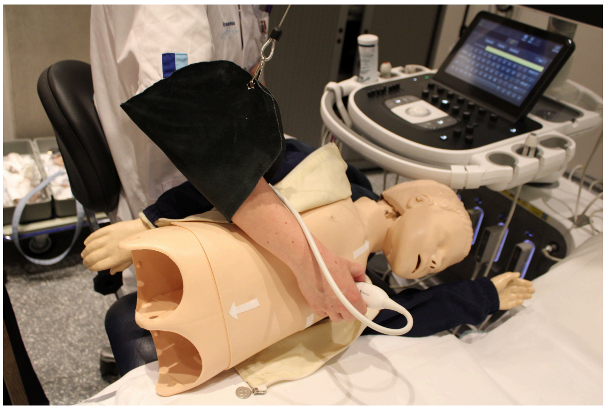


Figure 4.3h: Position when arm is not well suported

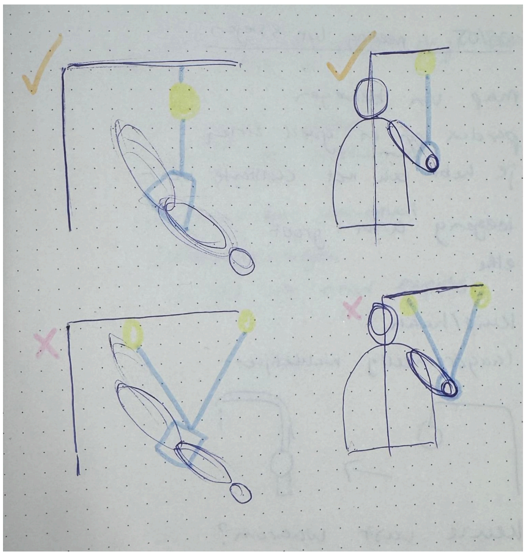


Figure 4.3i: Drawing explanation spring base alignment

Design Insights

- *It is important that the used can fully trust the product.*
- *User needs to be able to assist with two hands in an emergency situation.*
- *Alignment product should be easy to prevent using it wrong*
- *Should be easiliy cleanable*

Freedom of movement
All participants were satisfied with the freedom of movement afforded by the hanging support. All movements were possible to perform. The abdominal position (as shown in Figure 4.3j) was possible in the paediatric department, which was not possible with the leaning support. The ability to attach the product to the chair was seen as an advantage, as it allowed users to move their entire body during use.

Pressure points
Eighty-five per cent of participants said that they did not experience any pressure points or irritation when trying out the product. One participant noted that it was difficult to judge what strength the spring load should be set to. He said that 'when the spring load is set too high, you need to apply force to pull it down'. This is the opposite of what we want to achieve, so it is important that the spring load is set to the correct strength and is not set too high. The position furthest from the user should still be comfortable, and users should not need to apply force to counter the spring load. Figure 4.3k depicts setting the spring strength.

Additionally, one participant mentioned that, when mimicking pressing a skinfold, she felt the counterforce of the sling pushing her back. She said that this was a useful reminder that she was pushing, and that if it took too long, she would need to find another method or posture to acquire this image. Figure 4.3l depicts this technique.


Figure 4.3j: Moving from heart position into abdominal position

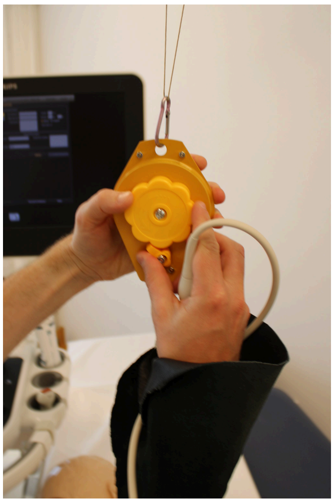


Figure 4.3k: Changing the spring strength

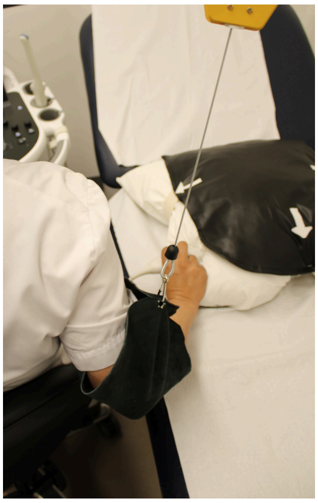


Figure 4.3l: Mimicking pressing in a skinfold

Design Insights

- *The product should stay attached to the chair.*
- *Setting the strength of the spring needs to be guided to prevent setting it too strong. Make sure that with the furthest point they don't have to pull the sling down.*

Material
Seventy-nine per cent of the participants liked the material that the sling was made of. The remaining participants suggested using a different material that would be less sweaty against the skin, for example looking into equestrian sports where they use neoprene with a gel layer.

Use entire day
Overall, participants reacted positively to the question of whether they would use the product for a whole day. Two participants suggested alternating between patients or using it for reintegration when someone was no longer able to perform an ultrasound. As the prototypes are intended for prevention rather than cure, the design needs to be attractive and easy to use.

Support
On average, this product received a support rating of 4/5. The main issue is getting the spring strength setting right. It is important to find the right balance between providing support and pulling your arm down easily. It is also important to have trust in the product. 'I was afraid of breaking the prototype,' said one participant. 'The final design should be really sturdy so I can fully hang on to it.'

Figure 4.3m: Wrapping the cord around the arm

General notes
It is important that the product does not interfere with the process. In both departments, a family member is sitting on the other side of the bed. Users should still be able to talk to them and make eye contact. It was advised that the product should be storable when not in use, as currently, the sling hangs in the user's face when moved away from the examination table.
It is also preferable if the user can put on the sling smoothly. Extra attachments such as Velcro are not favoured. Lastly, some users wrap the probe cord around their arm, as shown in Figure 4.3m. The design of the sling should take this into account.

Design Insights

- *The fabric of the sling should not feel sweaty.*
- *Make the product attractive and easy to use to encourage users to use it for prevention.*
- *Provide guidance on how to achieve the correct spring balance.*
- *The product should be sturdy enough for users to fully rely on it.*
- *The user should be able to wrap the cord around their arm or the design should take over this function.*

4.3.5 Discussion

The evaluation of the leaning and hanging support prototypes revealed contrasting strengths and weaknesses that shaped user experiences at both paediatric and gynaecology departments.

From the leaning support users appreciated the support it provided and its ability to help maintain better posture. This was especially at the paediatric department, where less macro movements are required during procedures. The benefit was overshadowed by discomfort, particularly pressure points in the armpit and upper arm area, which users anticipated could worsen over time. Additionally, the leaning device restricted freedom of movement, posing challenges especially in gynaecology. At the gynaecology repetitive macro movements are frequent. While the support was conceptually effective, its impact on mobility significantly reduced overall usability. Therefore there is a need for a redesign that reduces pressure in sensitive areas while enhancing movement freedom.

In contrast, the hanging support was praised for offering greater freedom of movement, which emerged as its key strength. Participants from both paediatric and gynaecology departments reported being able to perform all necessary scanning movements without restriction. At the paediatric department abdominal scanning was possible. In gynaecology, the sling supported users' repetitive motion workflows effectively. One participant even likened the experience to "relaxing in a hammock," reflecting a high level of comfort.

Additional strengths of the hanging support included the ability to attach the product to the chair, allowing the body to shift naturally with tasks. In general there was a positive evaluation of support and fit, particularly with the adaptation of placing the sling over the elbow in paediatrics. However, a few users noted that it took time to become comfortable fully leaning into the sling, and emphasized the importance of preventing improper alignment and avoiding excessive spring tension in future designs.

In summary, while the leaning support was effective in providing support, its drawbacks in comfort and mobility limit its use. The hanging support excelled in mobility and comfort, with minor design refinements needed to improve fit and alignment.

Limitations

First, the limited duration of use made it challenging for participants to evaluate long-term comfort, the development of pressure points, or the full-day use. Additionally, the hanging prototype was not mounted to the examination bed due to the need for portability across different hospital locations. This compromised the ability to assess product stability and real-life interaction during typical ultrasound procedure. Furthermore, testing was conducted on resuscitation dolls rather than real patients, meaning that dynamic factors such as patient movement were not fully represented. Although participants assigned a comfort score between 1 and 5, the study acknowledged potential bias in numerical ratings, placing greater emphasis on the qualitative feedback.

In the case of the hanging support, one limitation was that participants 21 and 22 tested the prototype without the spring base, which is a core component of the design. This likely impacted their user experience and makes their input less representative of the product's intended use. Additionally, while the design was tailored for the outpatient department, participants highlighted that working conditions in the ICU or inpatient ward present significantly worse postural challenges. Although these environments fall outside the scope of the current project, they represent important areas for future exploration, particularly if the support is to be adapted for other clinical contexts.

4.3.6 Conclusion: choice of concept

Based on the findings, the decision was made to proceed with the further development of the hanging support prototype.

The majority of participants (69%) preferred the hanging support concept, primarily because it offered freedom of movement and support throughout the entire procedure. As expected, the highest preference was observed in the gynaecology department, where 80% of participants favoured the hanging prototype. This aligns with the typically more dynamic motions involved in gynaecological procedures, compared to the 50% preference observed in the paediatric cardiology department.

In the paediatric department, a key concern about the hanging support was that the sling could tilt, affecting the quality of support. However, this issue is considered to be more easily resolvable through design improvements than the limitations observed in the leaning prototype, specifically reduced freedom of movement and pressure points. Furthermore, to deliver a product that could be used in other departments in the hospital, freedom of movement is a key criterion.

4.3.7 Conclusion on design insights

The design insights emphasize a user-centred approach that prioritizes ease of use, safety, and reliability. The product must limit the number of actions needed for operation, as excessive steps are perceived as annoying and discourage proper use. At the same time, it should offer enough adjustability to fit different users and situations, while making it easy to set correctly the spring tension, which should include clear guidance to avoid incorrect or overly strong settings.
To support user mobility, the product should be designed to stay attached to the chair and allow the patient to be positioned as close to the user as possible, without causing obstruction or limiting visibility. It is essential that the user can always see the patient clearly and have both hands available in emergency situations.

The arm support must not restrict blood flow, and the sling fabric should be breathable and non-sweaty while also being easy to clean with alcoholic wipes. The product must feel sturdy and trustworthy, giving users the confidence to rely on it during use. Misalignment should be difficult to achieve through intuitive design that guides correct setup and usage. Finally, the must be visually and functionally attractive to encourage frequent and correct use, ultimately improving both user experience and patient care.

4.4 List of requirements

The list of requirements represents the important findings the product must fulfil. These findings come from the observation, co-creations and expert testing.

They are divided in subcategories and the source is written between the brackets. These requirements give answer to the third Research question:

Functional Capabilities

- The product shall support use with patients in both lateral (LLD) and supine positions across paediatric and gynaecology departments. (CH 2.2)
- The product shall allow probe movement in the directions of rocking, tilting, fanning, and vertical movement. (CH 2.1)
- The product shall be compatible with various types of examination beds, including use with changing mats. (CH 2.2)
- The design shall not limit or obstruct the placement of a pillow underneath the patient, especially in the supine position. (CH 2.2)
- The product shall allow the patient to lie as close as possible to the user without obstruction. (CH 2.2)
- The product shall enable the user to assist with both hands in emergency situations without restriction. (CH 4.2)
- The product shall support the arm in all outer postures and provide movement. (CH 2.2)
  - Sideways: at least 466 mm or 508 mm (define final requirement based on use cases).
  - Forward/backward: at least 380 mm to 612 mm.
  - Support both static and dynamic movements.
- The product shall allow patients to lay their arm alongside their torso during use. (CH 2.2)
- The product shall not limit the clinician's ability to apply force during procedures. (CH 2.2)

Workflow & Usability

- The product shall minimize additional time required for sonography to support clinical adoption. (CH 4.3)
- The product shall require minimal setup time and as few user actions as possible for operation. (CH 4.3)
- The product shall be easy to align and quick to adjust to reduce the risk of improper use. (CH 4.3)
- The design shall be flexible to support smooth transitions between different postures and workflows.
- The product shall not block the clinician's view of the monitor during use. (CH4.1)
- The design shall accommodate right-hand gel placement for paediatric workflows. (CH2.2)

Ergonomics & Comfort

- The product shall not restrict user movement or obstruct blood circulation. (CH 4.1)
- The product shall accommodate a wide range of body types, including larger breasts. (CH 4.1)
- The product shall reduce the need to lean on the patient. (CH 2.2)
- The product shall support a natural working posture. (CH 4.1)
- The design shall offer adjustability for users between the 20th and 80th percentile. (CH 4.1)

Safety & Durability

- The product shall withstand a pulling force of at least 350 N. (CH 4.1)
- The product shall be durable enough to handle rough clinical use (“nurse-proof”). (CH 4.1)
- The product shall be perceived as stable, safe, and reliable. (CH4.1)
- The product’s spring mechanism shall be guided to prevent overextension. (CH 4.3)
- The design shall be heat-resistant (due to use of heating lamps). (CH 2.2)

Hygiene & Maintenance

- The product shall be made of materials that are cleanable with water or alcohol-based wipes. (CH 4.3)
- Maintenance shall be simple enough to be performed within the hospital setting. (Discussed with HSE officer)

Spatial Efficiency

- The product shall not obstruct walking paths or interfere with movement in the room. (CH 4.1)
- The design shall be compact and suitable for use in multiple ultrasound rooms. (CH 2.2)
- The product shall be mobile and usable in both paediatric baby and child setups. (CH 2.2)

Physical Design & Material Comfort

- All user and patient contact points shall be soft, free of sharp edges, and skin-friendly. (CH 4.1)
- Materials shall not stick to or irritate skin and shall be suitable for use with short sleeves. (CH 4.3)

Visual & Emotional Design (Paediatrics)

- The product shall maintain unobstructed face-to-face contact between user and patient’s parents. (CH2.2)
- The product shall use calming colors (e.g., blue) and have a non-intimidating, friendly appearance. (CH 5.3)
- The product shall avoid harsh noises (e.g., metal-on-metal). (CH 5.3)
- The product shall be introduced with a name, story, and interactive element to reduce child anxiety. (CH 5.3)

Business Constraints

- The product shall have a maximum target price of €500 to ensure affordability. (Discussed with HSE officer)

5 Lofius

This chapter explores the features of Lofius and the design decisions behind them. It begins with an introduction to Lofius, explaining its purpose and intended use. The product’s architecture is then discussed in detail, highlighting each component individually, along with the materials used and the production methods. In a separate section, the costs associated with these choices are outlined. The chapter also examines the product’s lifecycle, followed by an assessment of Lofius’s effects through an EMG test, comparing results with and without its use. Finally, the chapter concludes with a discussion on the feasibility and viability of the product.

5.1 Introducing Lofius

Lofius is an ergonomic instrument designed to provide support while allowing freedom of movement. This product features an adjustable spring system to fit all types of users. The Lofius compensates for the weight of the arm, resulting in relaxation of the shoulder muscles.

Designed with ultrasound procedures in mind, Lofius enables users to perform all the necessary movements for ultrasound examinations. Figure 5.1a shows Lofius in its natural habitats.

Beyond its ergonomic advantages, Lofius has a version designed especially for the paediatric department to help comfort children, which indirectly helps the user perform sonography more ergonomically.

Designed for outpatient environments, the Lofius easily attaches to an ergonomic stool, integrating seamlessly without taking up too much space. While seated on the stool, users have control and support wherever they need it.

Lofius gets her name from the genus name of the anglerfish family, *Lophius*. Many participants of this research saw similarities between the arm reaching over you, and the anglerfishes' "luring light bulb". Moreover, we can split up the name in Lofi, a sweet nickname, and US, which is an abbreviation of Ultrasound. Naturally, the similarities between Lofius and anglerfish should be restrained to the idea, as we will introduce it in setting were people should feel at ease.

Figure 5.1a: Lofius in context. Left: paediatric department. Right: gynaecology department.

5.2 Intended Use

Figure 5.2a shows the intended use steps of the Lofius. The use steps are as minimized as possible to make the adoptability of the product easier.

1 Align the pole with the examination table.

2 Ask the patient to move as close as possible. Set the examination table and the stool at the right height.

5 Place the arm through the sling with information sticker facing you.

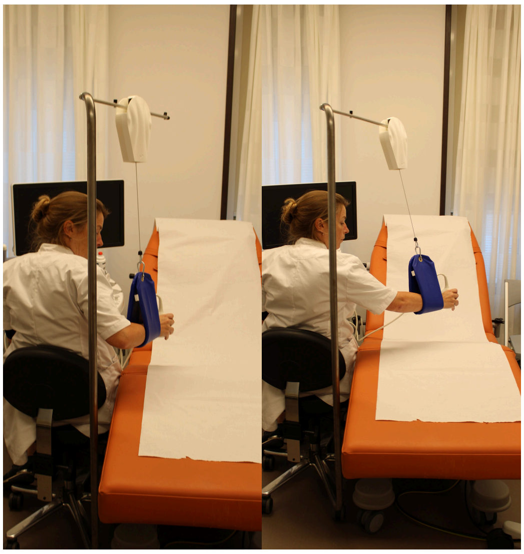
6 Check if resistance feels right and adjust if necessary.

Figure 5.2a: Steps of use for Lofius.

3 Move the arm above the area of interest of the patient.

4 Set the strength of the spring according to your weight.

7 Start to perform the ultrasound.



5.3 Product Architecture

Figure 5.3a illustrates the Lofius components. The three main parts are: the arch, the spring base, and the sling.

The arch consists of the connection module, the base module, and the arm module. The three modules are welded together. The hinge on top connects the base to the arm. The arch provides a stable base for the product.

The spring balancer comprises a spring module and a cover module. This cover has a neutral design and can be adjusted for children (see Paragraph 5.3.4). It has an informative side for the user and a neutral side for the patient. Spring resistance can be adjusted by turning the wheel in the middle of the spring balancer. The spring module is connected to a slider system that slides on top of the arm module.

The spring module is intentionally detachable to make repairs easier.

The sling is attached to the spring base via a hook. Similarly to the spring module, the sling has an informative side for the user and a neutral side facing the patient. From there, it is intuitive for the user to use the sling in the right way.

Figure 5.3a: Overview parts Lofius

5.3.1 The arch

The arch consists of three parts: the connection module, the base module and the arm module. Each module will be explained individually in this paragraph.

Connection module
The base of the stool is made of a gas lift. The type of gas lift used is often the Class 4 gas lift. The universal cylinders have an outer tube with a diameter of 50 mm and an inner tube of 28 mm (LANTAN, n.d.). Therefore the inner diameter of the connection module is 50 mm.

The connection consist of two parts with a hinge to make placement on the base of the stool easy. The quick release enables the user to install Lofius on different stools without using any tools which are not at hand at the departments. As further discussed in Section 5.5 the installation needs to be done by a HSE officer. To enable them to perform the installation alone they can hold the arch with one hand while clamping the connection module to the base with the other hand.

Material and production
The module will be made out of stainless steel using a CNC machine. This material is chosen because its corrosion resistance making it safe to use in a hospital setting. It is also a durable material with a smooth surface making it easy to clean (Unified alloys, n.d.). A technical drawing of the module can be found in Appendix L.
The attachment of the connection module and the the rest of the arch is done trough welding to create a strong bond. This should be done at an external partner as this can't be done at RdGG.

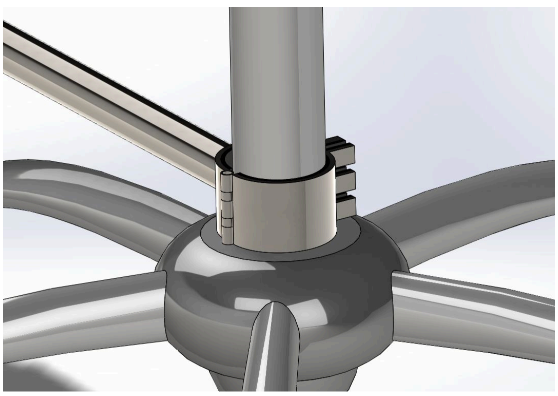


Figure 5.3b: Connection module design.

Base module
The base module is the biggest part of the arch and is made out of a long tube with a diameter of 25 mm. The base module had to be trustworthy was found during the expert testing, so therefore a thickness was chosen that is already used in the hospital for other trustworthy products such as an IV pole that also has a diameter of 25 mm (Provita medical, n.d.).
Appendix L shows all the measurements of the base module. The height was determined based on p20-p80 torso length plus the distance minimum and maximum sitting height of an average stool between 70-85 mm. The distance from the chair is chosen so tilting of the backrest is still possible.

Material and production
The base is made out of stainless steel tube with the same reasons why the connection module is made out of this material. The tube is bent in a 90 degrees angle using a bending machine. This can't be done at RdGG so the external partner should produce this part.
The base module is welded onto the connection module and the hinge connecting the base with the arm module.

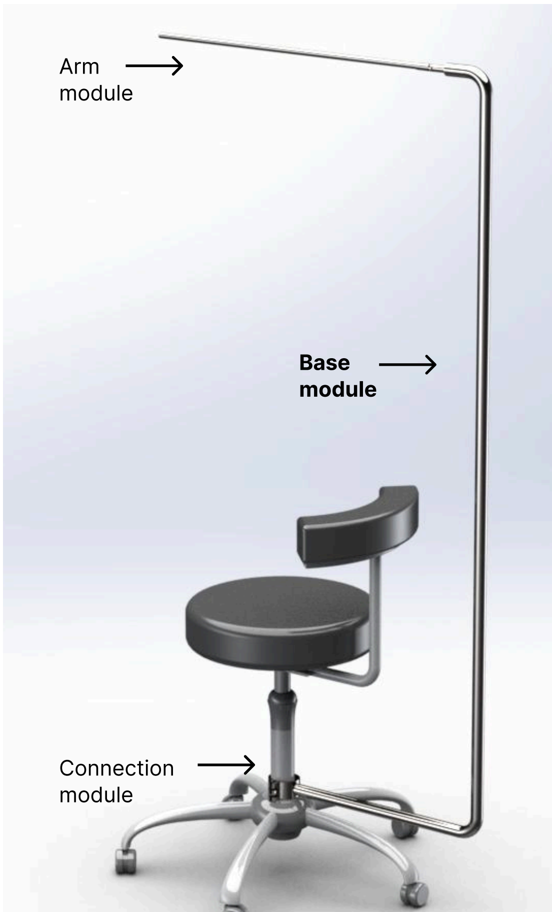


Figure 5.3c: Base module.

Arm module
The arm module consists of the arm, a hinge, two stopping ends and an end cover. Each of these parts will be briefly discussed.

The arm is made from a tube with a diameter of 12 mm. This thickness was chosen to give it a more elegant appearance but still be thick enough to withhold the forces which is further discussed in Section 5.7.

The arm is connected to the base by a hinge, see Figure 5.3d. The hinge enables it to turn through 90 degrees to each side, allowing the sling to be positioned above the patient, which was one of the findings form the expert testing. The hinge in combination with the sliding system gives the sonographer the flexibility to change positions during the procedure.

To prevent the spring from sliding off two stopping ends are placed. The distance between these two was based on the maximum movement field discussed in Section 2.2. Figure 5.3e shows the workings of the stopping ends.

The end cover is placed on the end of the arm to conceal the end of the arm. This also prevents the user from getting their finger stuck in the tube, see Figure 5.3f.

Material and production
The arm is again made of stainless steel. The arm is welded to the hinge connecting it to the base. The hinge is an off the shelf product. To enable the attachment to the base a spacer is used that need to be made on the lathe from a 23 mm rod. This connection is rendered in Figure 5.3g.

Figure 5.3d: The hinge and its way of movement.

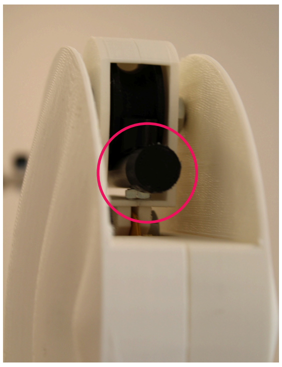


Figure 5.3f: Cover at end of arm circled in pink.

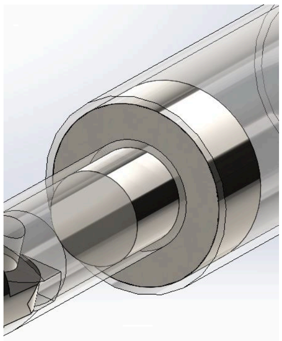


Figure 5.3g: Spacer between hinge and base module.

Figure 5.3e: The springbase sliding on arm.

5.3.2 The spring module

The spring module consists of the sliding module, the spring base and the base cover. Each module will be explained individually in this paragraph.

Sliding module

The sliding module consist of a diabolo wheel and a connection cover, see Figure 5.3h. To enable the spring base to be easily repositioned along the arm, a diabolo wheel is used that sits on top op the arm. This system is added to reposition the spring along the arm as this was one of the demands that came out of the EMG testing.

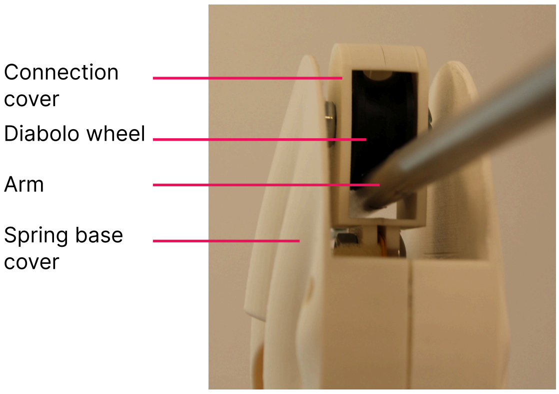


Figure 5.3h: Sliding module in context.

The wheel is designed to roll over the arm with a radius of 6,2 mm. A bearing inside the wheel makes movement easier. The wheel is connected to the spring base by the connection cover.

The connection cover consists of two half's that clamp together by two screws. One screw acts as the axis for the wheel and the other connects the connection cover with the spring base. Figure 5.3i shows the screw placement while Figure 5.3j show the two halves as an exploded view.

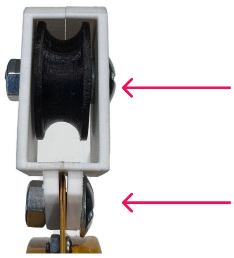


Figure 5.3i: Screws in connection cover.

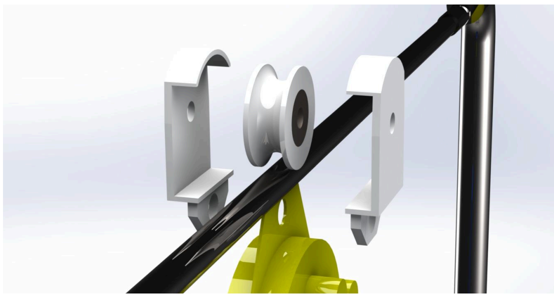


Figure 5.3j: Exploded view of connection cover.

Material and production

The diabolo wheel will be made of Polyoxymethylene (POM). This material was chosen because of is sliding properties making it move smoothly on the arm (Ensinger, n.d.). The diabolo wheel will be made with on the lathe out of a 40 mm rod, see Figure 5.3k. This manufacturing could be done by the medical technicians. When larger numbers are needed injection moulding could also be a good production method (Ensinger, n.d.).

The bearing wheels will be off the shelf product. Two can be placed perfectly next to each other.

The connection cover will be made out of PLA. For smaller numbers of products 3D printing would be a good production method. This could be done internal or by a partner. Again for larger number injection moulding could be the production method.

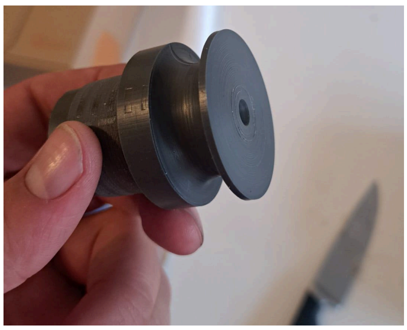


Figure 5.3k: Diabolo wheel made on the lathe.

Spring Base
The spring base is a mechanism that is already used in other industries, such as car manufacturing. Figure 5.3l shows the inside of a typical balancer. The prototype uses a QWORK spring balancer. The pink arrow shows the spiral spring that it winded by the yellow turning knob. The caring capacity of these springs is determined by the E-modulus of the material and the dimensions of the spring.

Setting strength
The spring balancer can support weights between 1.5 and 3 kg. Figure 5.3m illustrates the distribution of total body weight across the different body parts. It shows that the arm accounts for an average of 6.5% of body weight. Figure 5.3n illustrates the P20–P80 range for the weight of Dutch citizens. Therefore, the lightest setting should be 3.77 kg and the heaviest 5.98 kg.

To avoid the muscle compensating for the spring by pulling it down, roughly half of the weight should be compensated for, i.e. 1.8–3 kg. Therefore, the spring base covering 1.5–3 kg is the best fit. If clinical studies subsequently reveal that a lighter or heavier spring is necessary, it can easily be replaced.

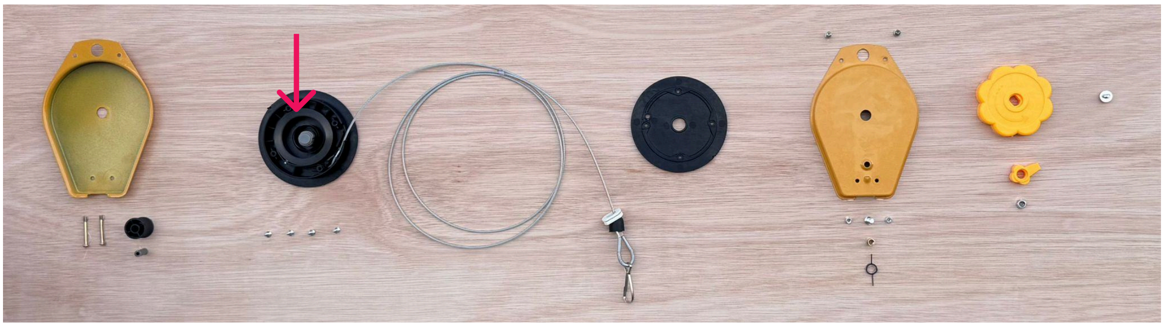


Figure 5.3l: Cross section of spring balancer, arrow points to the actual spring (Conductix-Wampfler, n.d.).

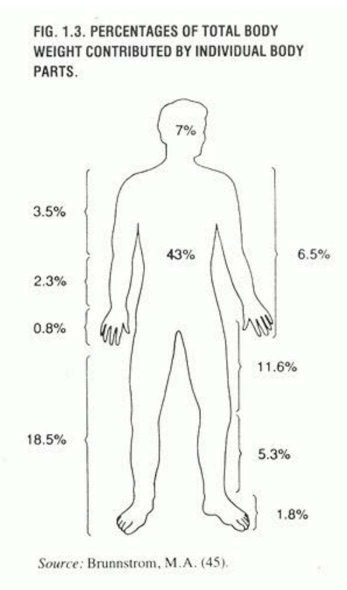


Figure 5.3m: Percentage of total body weight contributed by individual body parts (Body Composition, n.d.).

populations	Dutch adults 20–30, female	Dutch adults 31–60, mixed	Dutch adults 31–60, male
measures	P20	P50	P80
Body mass (kg)	58	76	92

Figure 5.3n: Body mass in kg (DINED, n.d.).

A test was conducted to determine how many settings where necessary to distribute the 1.5 kg difference between p20-p80. This test can be found in Appendix M. The test resulted in eight different settings. Figure 5.3o1 shows the body mass with the corresponding settings.
One will be the setting with the least resistance and eight will be the setting with the most resistance with the difference shown in Figure 5.3o2.

A table showing weight and strength settings will be placed on the base cover. A warning sign will also be placed to remind users not to set the spring too strongly.

The settings numbers will be placed on the turning knob. The white arrow points out to the setting the spring is in. The numbers of the settings are placed on the turning knob with stickers, making sure that it the setting it is in is always readable for the user.

To be sure that the knob won't turn outside these eight settings, an protrusion is placed on the circle of the first setting (circled in pink in Figure 5.3p).

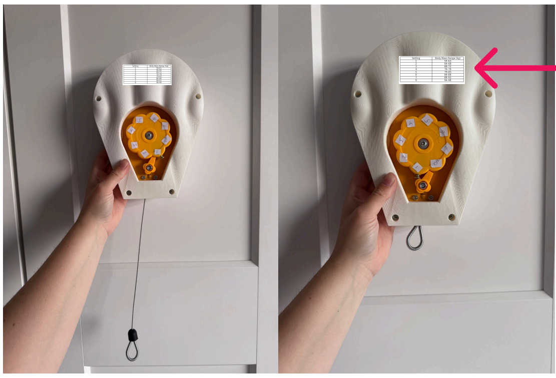


Figure 5.3o2: Difference resistance setting 1 on the left and setting 2 on the right.

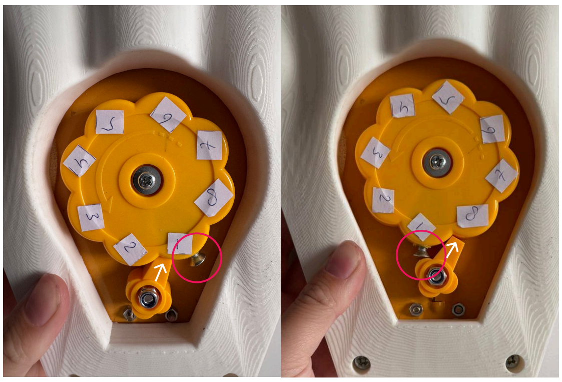


Figure 5.3p: Placement of lumb circled in pink with setting 1 on the left and setting two on the right.

As show in Figure 5.3l, the yellow knob a part that can be taken off. This could be replaced by a knob with the protrusion already integrated into the design.

Material and production
The spring base is a off the shelf product that is available with three different load capacities: 0.5-1.5, 1.5-3 and 3-5 kg.
The table will be a sticker that can be printed and placed on Lofius.
The protrusion is now made of bolt that is placed in an insert inside the turning knob. The entire knob can also be replaced by a 3D printed part including the protrusion and the numbers of the settings as shown in Figure 5.3q.

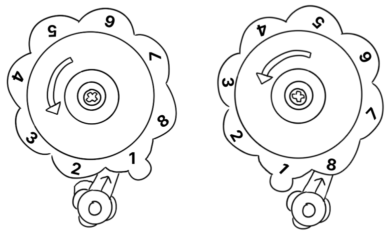


Figure 5.3q: Incorporated protrusion in knob design.

Setting	Body Mass Range (kg)
1	59–63
2	64–68
3	69–73
4	74–78
5	79–83
6	84–88
7	89–93
8	94–98

Figure 5.3o1: Table with the distribution of settings according to body ass.

Base Cover

The base cover is made to protect the springbase. Its shape is inspired by a combination of a shell and a hot air balloon. The shell design was inspired by the name Lofius and the underwater world, as explained in Section 5.1. The air balloon was chosen to fit the theme of the paediatric department, as explained in Paragraph 5.3.4.

Both the air balloon and the shell have divergent shapes and stripe structures shown in Figure 5.3r, which were ideal to combine. Both the paediatric and gynaecology departments will have the same cover, but add-ons will be available for the paediatric department.

Figure 5.3r: shape inspiration of the cover

The shell consist of a patient side and a user side. The patient's side is neutral and contains a logo of RdGG. The user's side has the access to the turning knob to set the strength of the spring. The different sides are shown in Figure 5.3s.

The two halves of the cover are connected with each other by four screws. Inserts are placed in the patient's side as shown in Figure 5.3t.

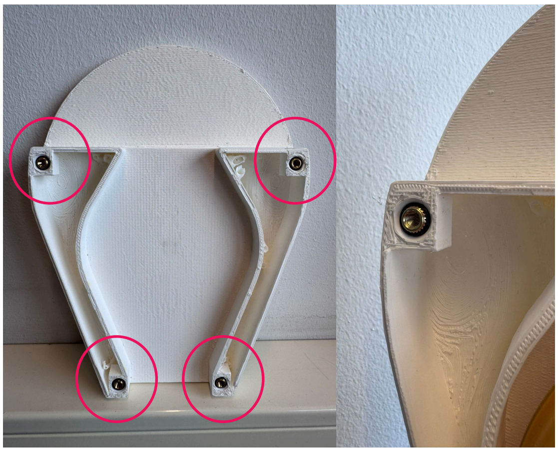
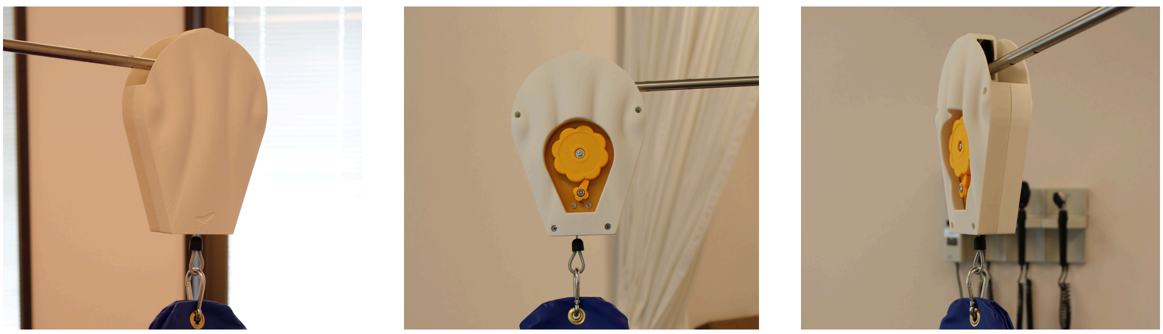


Figure 5.3t: Inserts placement and close-up.

To prevent dust from getting into the holes where the bolts are put in, plugs will be pressed in for example the ones in Figure 5.3u. It is important that they are pressed in so they can't come loose during the procedure, to prevent chocking hazards.

Figure 5.3u: Hole plugs to prevent dust coming in.



Patient's side | User's side | Side profile

Figure 5.3s: Base cover features.

The base cover will be available in a variety of colours. To fit the aesthetic of RdGG it would be advised to use the colours from the corporate identity as shown in Figure 5.3v.

Figure 5.3v: Corporate identity colours of RdGG.

It is advised by the the hospital's pedagogical staff to use calming colours such as blue and white. Impressions of the possible end products can be seen on the right in Figure 5.3.w.

Material and production
The base cover will be 3D printed from PLA. This can be done in-house in the workshop at RdGG for the testing period. In a further stadium this can be outsourced through a collaboration for example with the company Oceanz who produces a lot of 3D prints for the medical field.

Figure 5.3w: Renders of possible final version of base cover in different colours.

5.3.3 The sling module

The sling module is connected with a clip to the spring module. The sling is positioned on the lower arm, 2-3 cm from the tip of the elbow. This distance is chosen to prevent the user from placing the sling to close to the wrist. This would limit the movement of the wrist and create an lever of the arm pulling it the wrong way.

The sling also has a user and an a patient side shown in Figure 5.3x. On the user side a drawing is shown of the placement of the sling on the lower arm. The drawing shown in Figure 5.3y give directly an indication on which side the user should enter the sling. The patient side is again neutral.

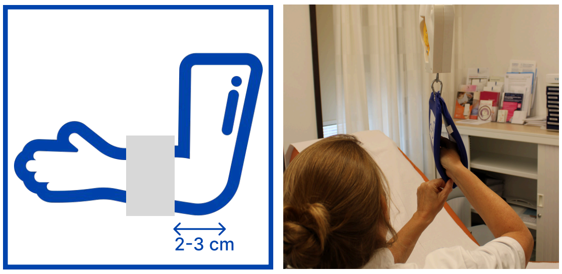


Figure 5.3y: Left: instruction drawing. Right: how to enter the sling.

To prevent from the sliding upwards, foam is placed as a lining to create more grip on the arm as it folds around it. Next to this, the lining creates an opening which is a clear use cue that it is an entering point.

Material and production

The sling is made of a medical-grade synthetic leather. This material is made 3% PVC-PU finish, 12% CO/PES knitted fabric and 85% PCV compound. The material is long lasting, resistant to oil, antibacterial, tear resistant and easy to clean (SKAI leer, n.d.). The outside is assembled on the sewing machine. It is sewed together inside out and then the 1 cm foam lining is placed inside. Next, the holes will be made and line rings are pressed on. These steps are shown in Figure 5.3z.

Figure 5.3z: Overview of the steps for production of the sling.

Patient's side

User's side

Side profile

Figure 5.3x: Sling design from different sides.

5.3.4 Paediatric design

Many medical devices are modified to appear less frightening to children. Figure 5.3aa shows a few examples.

The Lofius prototype was discussed with the hospital's pedagogical staff. The most important thing is to consider the name, shape and story. The name should be catchy to help introduce the product. The shape should be appealing and act as a distraction. Lastly, a story is an easy way to introduce the product to children, making them less afraid of it.

Logically, the product should not have any sharp or pointy edges. Avoid sounds such as metal on metal. Allowing children to touch the product is a good way to make them comfortable. Make sure this is possible and that it will not hurt them.

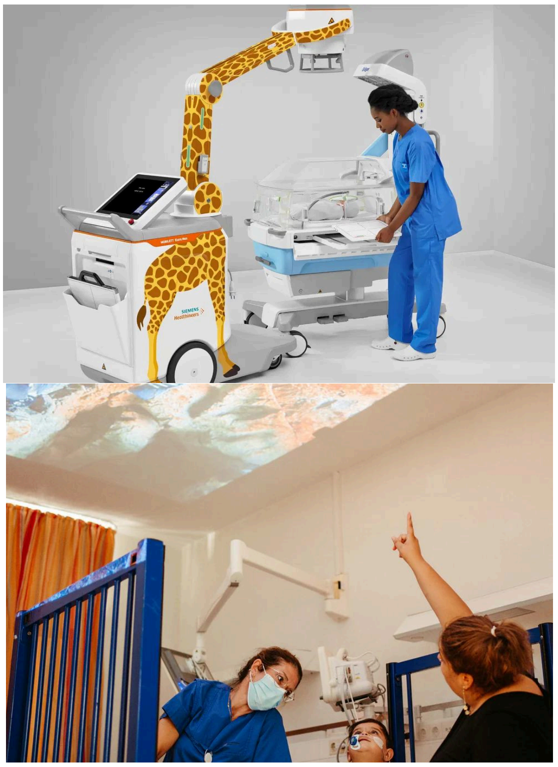


Figure 5.3aa: Examples of medical devices for children. Top (Siemens, n.d), Left (Qwiek, n.d.).

Lofi the hot air balloon
Also Lofius has a story. The spring cover is designed to look like a balloon with the sling as its basket. An hot air balloon is already incorporated in the décor of the room and department, see Figure 5.3bb. Therefore Lofius will fit right in.

Figure 5.3bb: Lofius with the hot air balloon in the background.

In Dutch it will be called: *Lofi de Luchtballon*. The paediatrician can introduce the support tool with the following story:
"This is Lofi the hot air balloon. She is going to help me perform the ultrasound. I will put my arm in the basket and ask Lofi to steer me. Together we will go on a balloon ride at dusk. I will turn down the lights and you have to help Lofi steer through the stars with your eyes. You have lay very still otherwise Lofi does not know where to go. Can you help me?"

The stars can be projected using a beamer. Currently they are testing at the department with the Capsule Nebula. In a future stadium the projector could be placed on top of the Lofius to have a perfect projecting.

Cover end of arm
The end of the arm is now covered with a closing lid. To even fit more the aesthetic of an air balloon an sun or cloud could be placed at the end of make the design even friendlier.

Sticker
To give Lofius a personality, a sticker of a face could be added as shown in Figure 5.3cc.

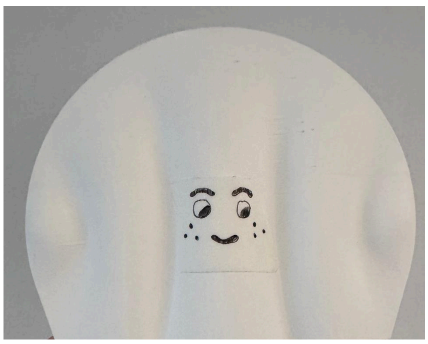


Figure 5.3cc: Sticker of face.

5.4 Estimated production costs

If Lofius were to be integrated in the clinical workflow, it is important to look at the financial burden. The production costs for the product vary depending on whether it is manufactured in-house or by external partners. Below is an overview of both approaches, including cost estimations and key considerations.

In-House Production

In-house production primarily involves material costs. The estimated cost for producing one unit of Lofius is €186.

The frame will be constructed in the workshop, with welding performed free of charge by a colleague who is also a qualified Medical Technician. The RdGG workshop is equipped with two Ultimaker 3D printers for component fabrication.

The only notable uncertainty is the sewing of the sling, as the hospital does not currently have a department dedicated to this task. This step would therefore need to be outsourced. Assuming it takes approximately one hour, the estimated cost is €21 per sling.

External Production

Estimating the costs for external production is more complex. Material costs are assumed to remain comparable; however, other factors may increase the overall expense. For instance, when the cover is produced by Oceanz, the price is already higher than for in-house manufacturing. This was determined using Oceanz's online quotation tool. Establishing a formal partnership with Oceanz may help reduce these costs.

Additional production steps such as bending, welding, and lathing can be outsourced to Van der Velde Delft. A quotation request was submitted using the technical drawings provided in Appendix L. Van der Velde recommended using AISI 316 stainless steel over AISI 304 for better suitability in a hospital environment, which contributes to higher costs.

Part	Module	Material	Dimensions	Price material (incl. btw)	Who produces	Price production	Link
Arch							
	Base	AISI 316 (SS)	25 x 2 x 2000 mm	71,93	Inhouse welding and bending	0	https://www.rvs-|
	Connection module	AISI 316 (SS)	140 x 80 x 2 mm	4	Inhouse lathing, welding and bending	0	https://metaalsh
	Arm	AISI 316 (SS)	12 x 2 x 520 mm	8,55	Inhouse welding and bending	0	https://www.rvs-|
	Hinge	AISI 304 (SS)	12 mm	9,34	welding to other parts	0	https://www.rvs-|
Spring							
	Springbase	-	1,5 -3 kg	12,99	Change knob, inhouse	0	https://www.ama
	Base cover	PLA	1 kg PLA	18,95	3D printed in hospital	0	https://www.123-
Sling							
	Medical leather	PVC	1 meter	14,95	Sewing	21	https://www.skai
	Rings	AISI 304	1 needed, 50 in a pack	11,49	Inhouse	0	https://www.prax
	Foam	Polyether	500 x 2 mm	3			https://schuimwi
Screws etc				10			
Total				165,2		21	
Product Costs				186,2			

Figure 5.4a: Table wit cost estimation Lofius with in-house production.

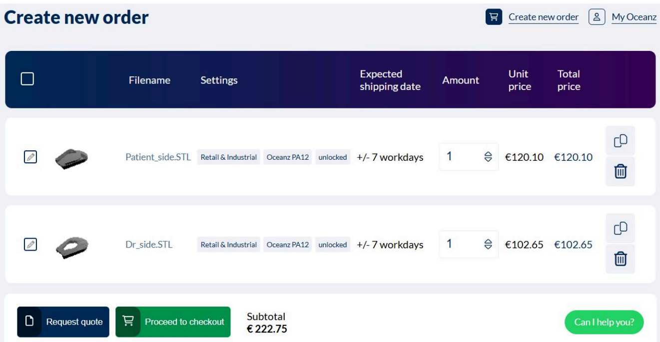


Figure 5.4b: Cost estimation of Lofius' covers by external manufacturer Oceanz.

5.5 Product Life Cycle

In order to determine how Lofius will be integrated into the RdGG system, the course of action for an ergonomic chair is explained. Using this knowledge, a plan is set up for the Lofius request.

Request an ergonomic chair
At RdGG, sonographers can request an ergonomic chair from the HSE department if they have chronic conditions. The HSE coordinator will visit the worksite to determine whether a chair is necessary and which type would best suit the individual. External tools are ordered when the basic settings of the chair do not suffice.

Request Lofius
Lofius is designed to prevent WRMDs in the shoulder. Therefore, the product should be used before chronic conditions appear. The HSE coordinator will decide whether the product is suitable for use in the department. As the product is designed for the gynaecology and paediatrics department, further testing must be conducted before it can be used in other departments. Observations from other departments suggest that the product could also be of interest to departments such as radiology.

Lofius is designed to fit all height-adjustable chairs in the hospital. In the paediatric department, only one person performs ultrasounds and they have a personal ergonomic chair. Therefore, the Lofius will always be attached to this chair.

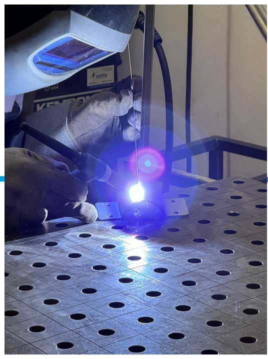
At the Department of Gynaecology, two ultrasound rooms are used simultaneously. Therefore, a Lofius should be available in each room.

Product Journey Map
The Product Journey Map shows the steps involved in installing Lofius at the departments. The process differs depending on whether the product is produced in-house (with the help of partners) or externally. It is expected that the product will first be produced in-house and tested before seeking an external party to take over the design. The product journey maps are shown if Figure 5.5a and Figure 5.5b. It is remarkable to see that with external production more steps are involved and more different stakeholders are involved in the process. It it good to remember that with the in-house production someone needs to be responsible for the coordination of the production and getting the product at the right places. This will be most likely the HSE coordinator.

End of life
As Lofius is made for the biggest part of stainless steel and plastic. Stainless steel is a durable material but also 100% recyclable with keeping its properties after recycling (Thyssenkrupp, n.d.). The covers made of plastic can be recycled into new filament but this needs special equipment (3devo, 2024). The part with the most maintenance needed is the spring base as it is expected that fatigue will occur of the flat spiral spring (Keneng, 2024). This part can be replaced by the technicians in the hospital or a new springbase has to be ordered.

Product Journey Map
In-house production

HSE coordinator will determine what departments need Lofius and how many.

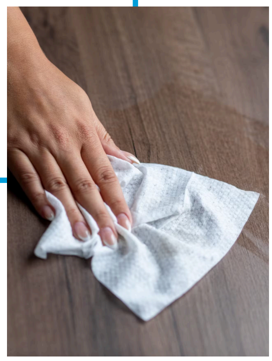


Lofius wil be produced in house but with help of external partners. The spring base will be a purchased part.

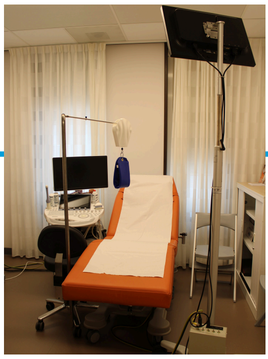
HSE coordinator will install Lofius and explain workings.

At the paediatric department, one will be permanently placed on the personal chair of the paediatric cardiologist.

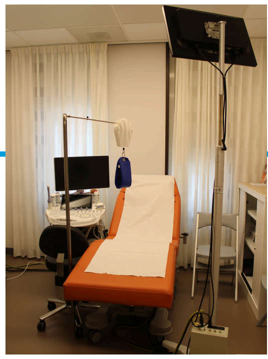
The personal chair with Lofius will be stored at office on the department and placed in the ultrasound room by the doctor's assistant.



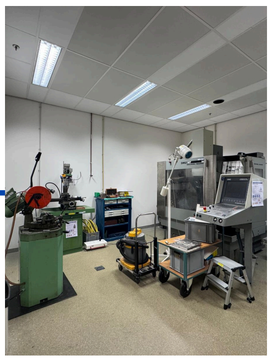
Lofius will be cleaned after a full day’s use with wet wipes or microfibre cloth by the doctor’s assistant



At the gynaecology department, two will be permanently placed on an ergonomic chair in each ultrasound room.



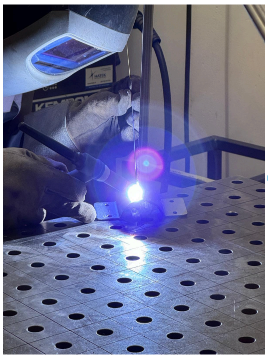
The chair with Lofius will be stored in the ultrasound room.



When problems occur, the medical technicians can replace parts to keep the product up and running.

Figure 5.5a: Product journey map when Lofius is produced in-house,

Product Journey Map
External production



Lofius wil be produced by a manufacturer in medical tools/furnature.

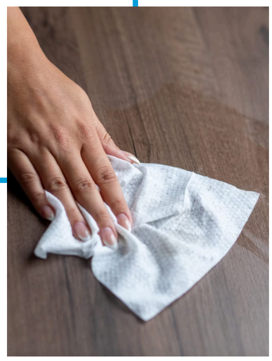
HSE coordinator will determine what departments need Lofius and how many.

Facilities officer will order Lofius at manufacturer and deliver at department.

HSE coordinator installs Lofius and explains workings.

At the paediatric department, one will be permanently placed on the personal chair of the paediatric cardiologist.

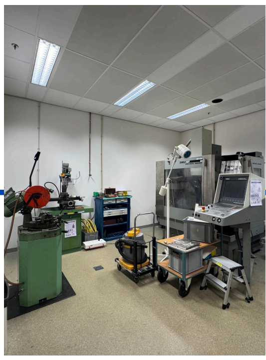
The personal chair with Lofius will be stored at office on the department and placed in the ultrasound room by the doctor's assistant.



Lofius will be cleaned after a full day’s use with wet wipes or microfibre cloth by the doctor’s assistant

At the gynaecology department, two will be permanently placed on an ergonomic chair in each ultrasound room.

The chair with Lofius will be stored in the ultrasound room.



When problems occur, the medical technicians can replace parts to keep the product up and running.

Facilities officer will order spare part at manufacturer if this is necessary.

Figure 5.5b: Product journey map when Lofius is produced externally

5.6 EMG test with Lofius

The same EMG test as in Section 2.3 is performed a second time, this time with the support of Lofius. EMG is used to observe muscle activity during sonography and to analyse how Lofius's intervention affects muscle activity in each posture. In addition to the EMG test, goniometers are used to measure the angles of the shoulder in the different postures. Only the shoulder is measured this time, leaving the arm free of cables and making the use of Lofius as realistic as possible.

The aim is to measure the muscle activity and angles and to establish whether Lofius reduces muscle activity compared to the results presented in Section 2.3.

5.6.1 Method

Participants
The same two participants who took part in the first EMG test were recruited to enable comparison between the results.

Material and procedure
The same materials and procedures were used as in the original EMG test, except that the goniometer was not placed on the wrist and there were no EMG sensors on the flexor digitorum profundus. The two muscles observed were the supraspinatus and the upper trapezius. The supraspinatus and trapezius were selected as they are the primary muscles involved in arm abduction, alongside the deltoid and serratus anterior (Lam & Bordoni, 2025). Both the muscles are highlighted in green in Figure 5.6a. Abduction was identified as a risk factor through literature and observation, and was therefore measured.

At the paediatric department, the test was split into two again according to the LLD and the supine position of the simulated patient. This was done to facilitate comparison between the two tests.

To recap, the participants were asked to perform an ultrasound on a simulation patient to represent a GUO at the Department of Gynaecology and a full check-up of the heart at the Department of Paediatrics with support of Lofius. They were also asked to think aloud and to mention when they changed their posture so that the button could be pressed accordingly. Any pain or irritation experienced by the participants was noted down on a comfort map shown in Appendix K.

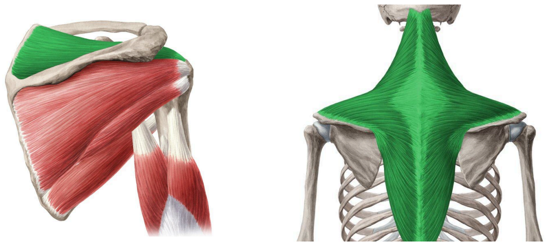


Figure 5.6a: Left to right: supraspinatus, trapezius

Ethics
The same precautions were taken to protect user privacy, and informed consent was obtained from both the user and the simulation patient.

Analysis
The same analysis will be performed as in the original test, except that the wrist and flexor will not be analysed. This will be done in MATLAB. First, the EMG and goniometer data from this test will be analysed in isolation, and then compared with the results from the original test to see if using Lofius results in less muscle activity.

Add how comparison is made between two emg tests

5.6.2 Results LLD position paediatrics department

To compare the results of the previous EMG test this test was also split into LLD position and supine position.

Findings
The button was pressed 6 times. The first and last press was for the start and ending and the 4th for adjusting the sling. Figure 5.6b shows the four postures. Note that posture four takes place after the button is pressed for the fifth time.

Abduction
As was mentioned in Chapter 1, arm abduction greater than 30 degrees is a risk factor for WRMD. Figure 5.6c shows the abduction/adduction of the shoulder for the whole LLD part of the ultrasound. The blue box represent the abduction area. The black line represent the 30 degrees mark. As shown in Figure 5.6c, for 72% of the time, the abduction greater than 30 degrees.

Note that the right y-axis depicts the angle of abduction/adduction (or flexion extension for other measurements). This is in correspondence with further plots, where we will have the EMG results on the left axis.

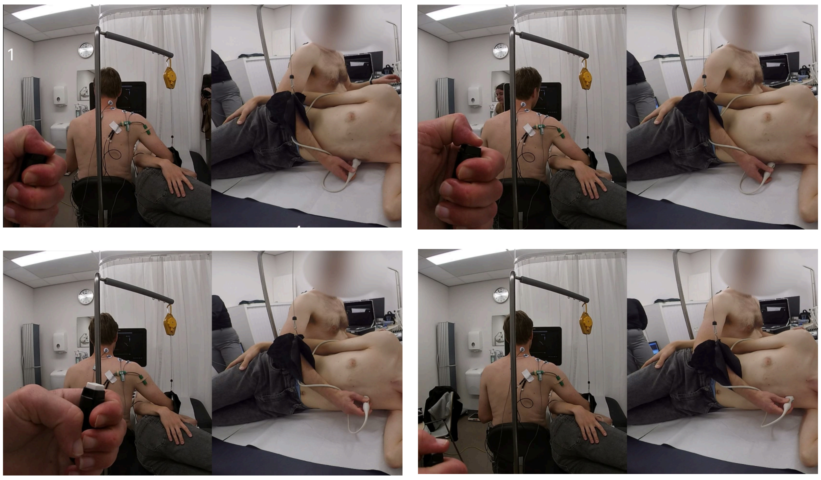


Figure 5.6b: Four postures during the ultrasound

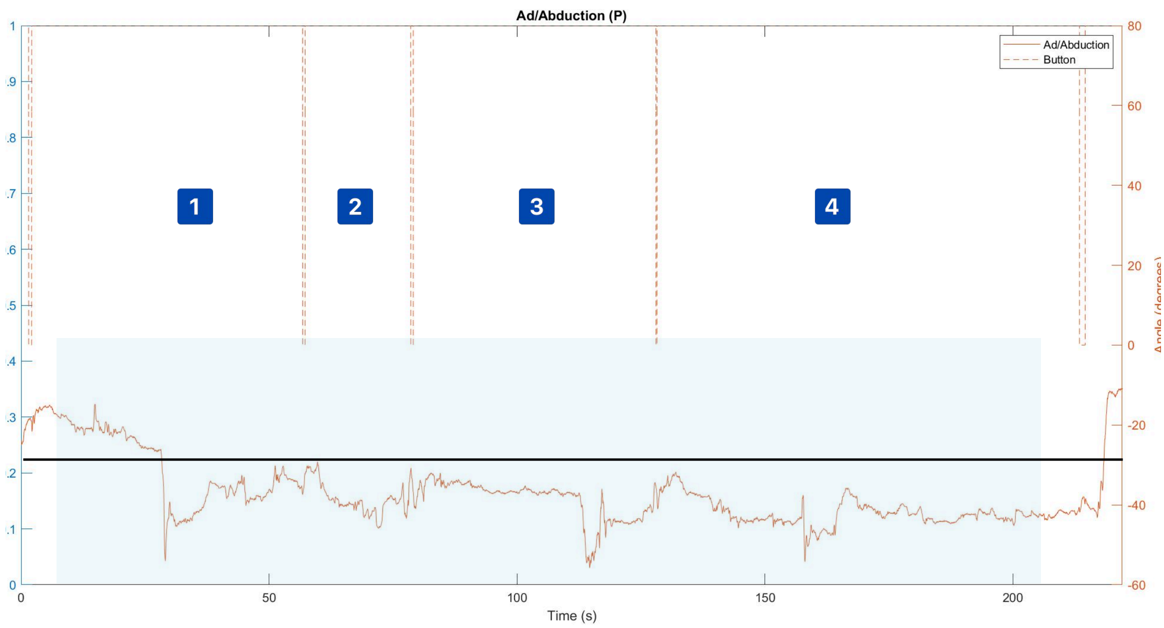


Figure 5.6c: Abduction of arm over time for the LLD part of the paediatric ultrasound examination.

Supraspinatus

In the LLD position, the supraspinatus is active in all the positions. The biggest peaks are seen when changing from position as the arm is then lifted. This can be seen in Figure 5.6d.

Posture one shows the correlation between angle and muscle activity. The supraspinatus is very important for lifting the arm so you see more activity at the beginning of the abduction. The high peak at posture 3 is due to adjusting the position of the sling.

Trapezius

In the LLD position, the trapezius activity is constant in all the different postures, with minor peaks when changed from posture. The same peak in position three is showing when te participant is adjusting the sling. See also Figure 5.6e.

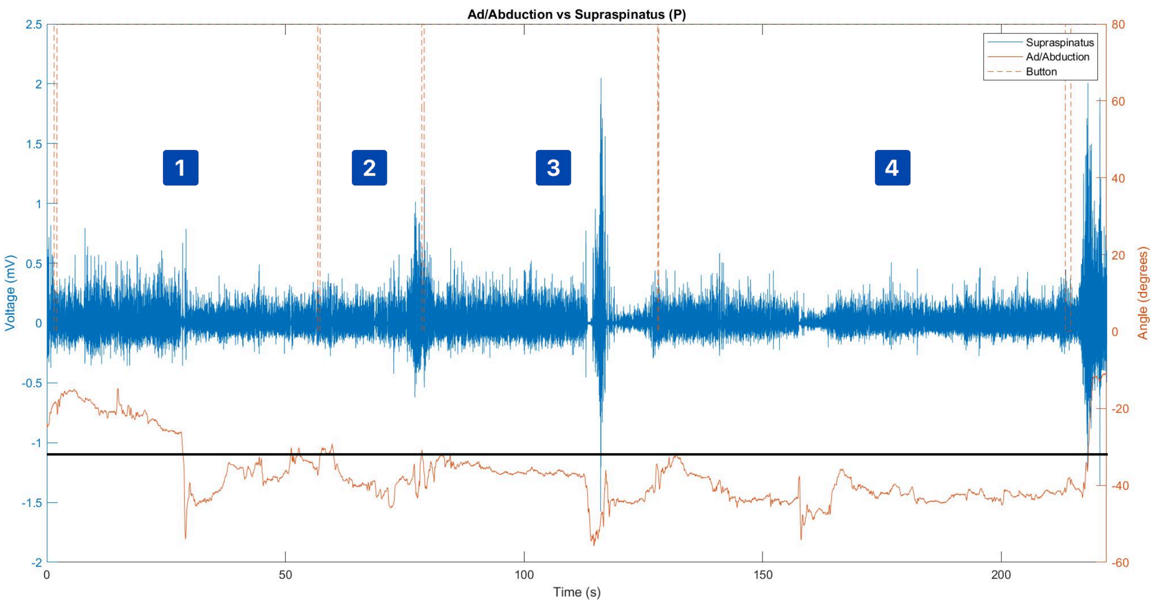


Figure 5.6d: Muscle activity of supraspinatus plotted against ad/abduction.

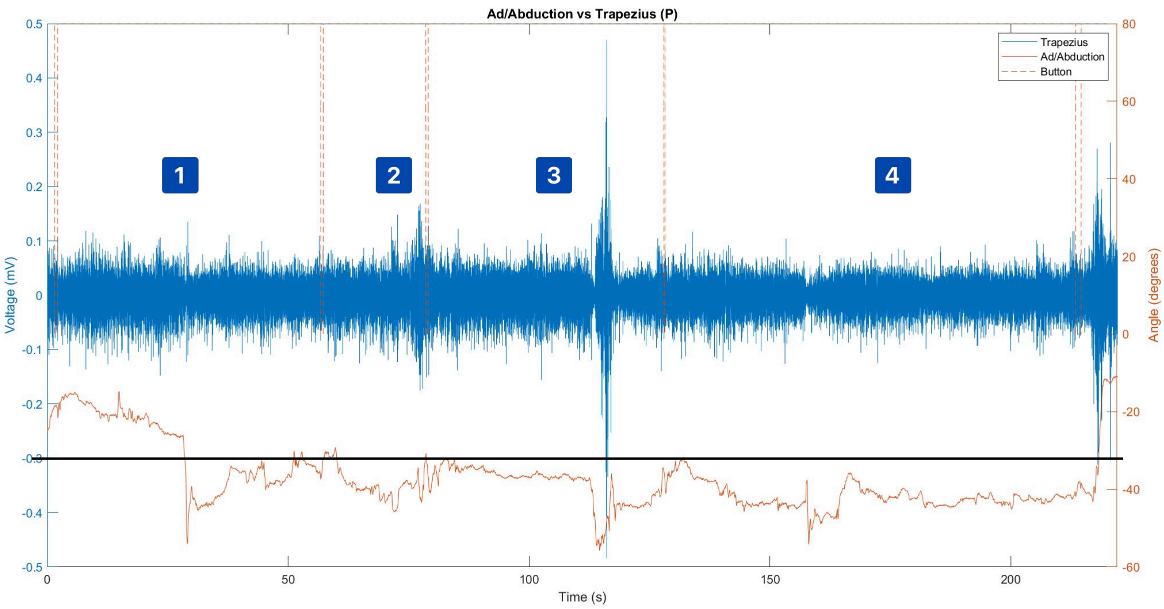


Figure 5.6e: Muscle activity of trapezius plotted against ad/abduction.

5.6.3 Results supine position paediatric department

Findings paediatric department supine position

The button was pressed 8 time representing 6 postures of the participant. Figure 5.6f shows the 6 postures. These postures will be all discussed for abduction and muscle activity.

Figure 5.6f: Six different postures in supine position.

Abduction

Figure 5.6g shows the abduction/adduction of the shoulder muscle. The light blue box represent the abduction area, the dark blue box represent the adduction area. The black line represent the 30 degrees mark. As shown in Figure 5.6g is 5% of the time the abduction greater than 30 degrees. This is significant less then in the first part of the test.

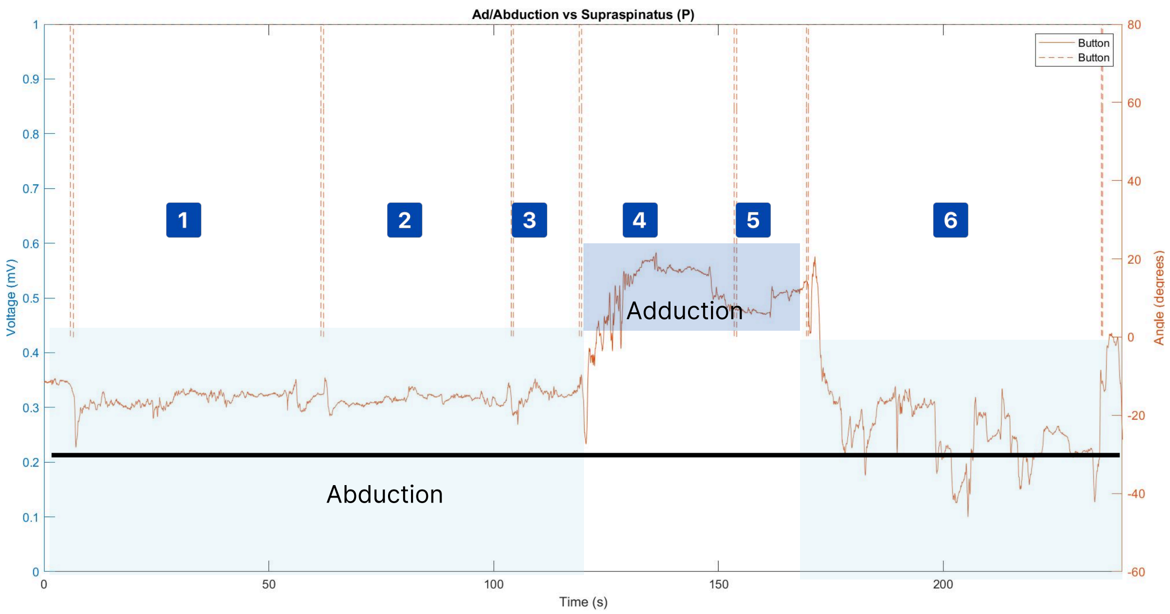


Figure 5.6g: Abduction of arm over time for the supine part of the paediatric ultrasound examination.

Supraspinatus

In the supine position the muscle activity in the first three postures did not exceed the 1 mV, as can be seen in Figure 5.6h. This was the same for in the LLD position. The peak at the beginning of the fourth position can be explained because the participant was moving into the position and moving himself backwards creating a lot of activity as well as adduction above 20 degrees. When using force at the abdomen at position 6, the abduction is above the thirty degrees.

Trapezius

The activity of the trapezius is constant the entire test with again the bigger peak at the beginning of the fourth posture due to the fact that the participant needed to move backwards for this position. See also Figure 5.6i.

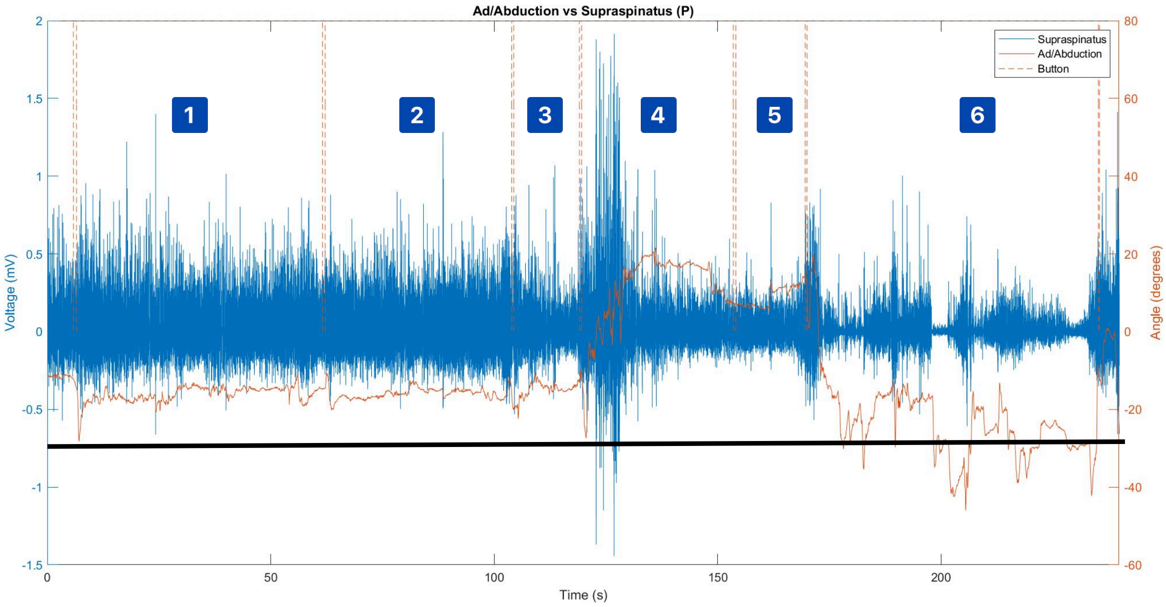


Figure 5.6h: Muscle activity of supraspinatus plotted against ad/abduction.

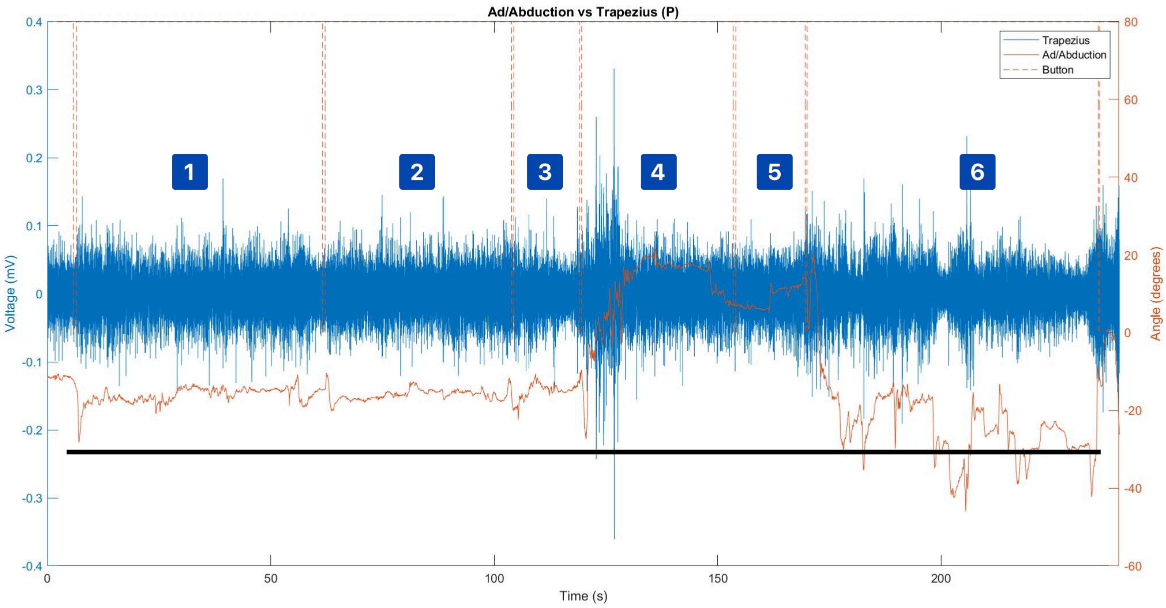


Figure 5.6i: Muscle activity of trapezius plotted against ad/abduction.

5.6.4 Results gynaecology department

Findings
The button was pressed 44 times representing a lot posture changes of the participant. These changes consist of bigger and smaller changes. A detailed list with explanations of all the 44 buttons pressed can be found in Appendix O.
The same three extreme postures from the RULA have been again used to analyse the different muscles.

Three postures
Figure 5.6j shows the three postures that are already discussed in Section 2.3.
These three postures will be analysed on abduction and their muscle activity.

Abduction
Figure 5.6k shows the activity of the supraspinatus and the abduction/adduction of the shoulder.

Almost the whole time the arm is abducted. As shown in Figure 5.6k, for 57% of the time, the abduction greater than 30 degrees.

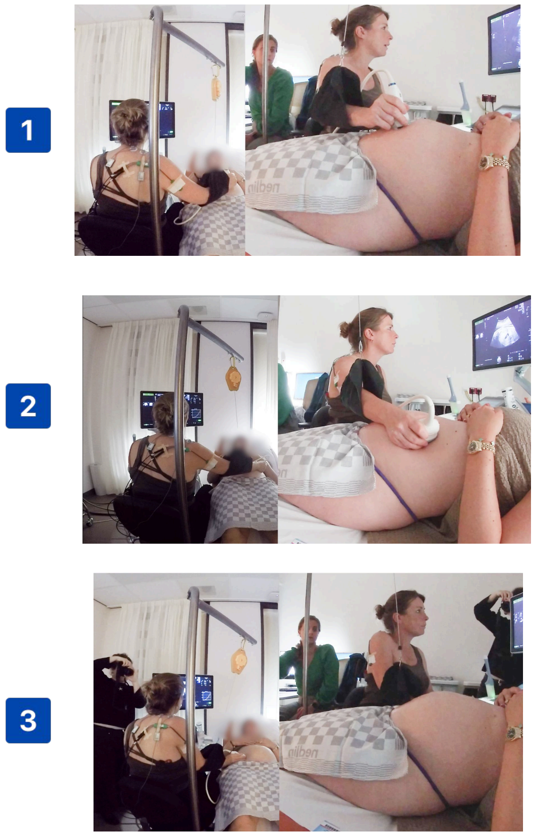


Figure 5.6j: Three extreme postures in gynaecological examination.

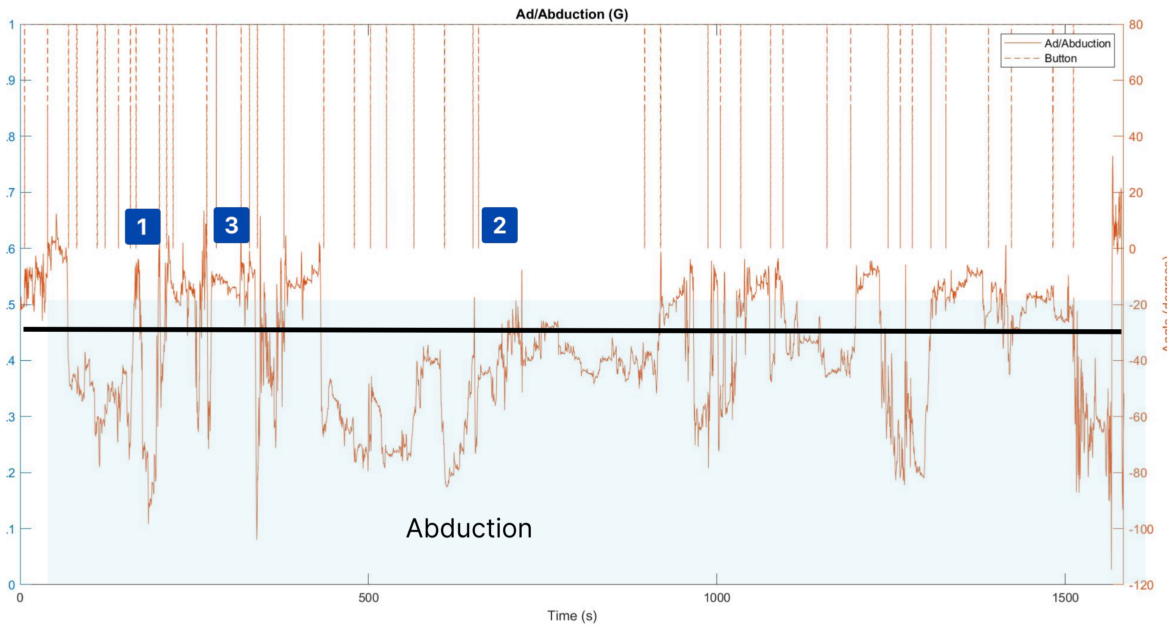


Figure 5.6k: Abduction of arm over time for the gynaecological ultrasound examination. Marked are the extreme postures.

Supraspinatus

Figures 5.6l.1-3 shows the activity of the supraspinatus and the abduction/adduction of the shoulder at the three extreme points, which are depicted in Figures 5.6m.1-3.

In the first posture the activity is average. The user noted that this position is very comfortable of perform the ultrasound with support of Lofius.

At the second posture, the abduction is 2 times larger while the muscle activity is roughly the same.

In the third position the muscle activity was lower compared two the first two, which was expected because the arm is next to the body of the participant.

The big peaks at the end of the graph is a moment when changes needed to be made to the position of the spring base so the arm is held up high. This is not relevant for our analysis.

1

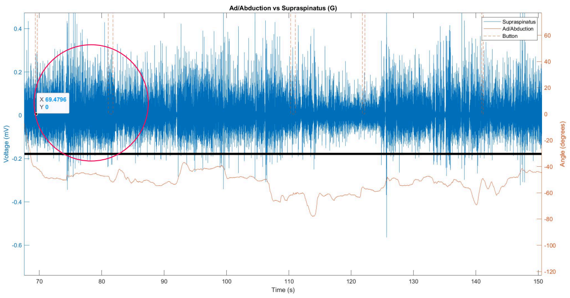


Figure 5.6l.1: Muscle activity supraspinatus with posture one circled.

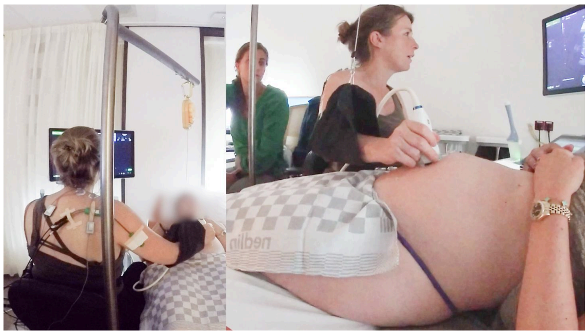


Figure 5.6m.1: Posture one.

2

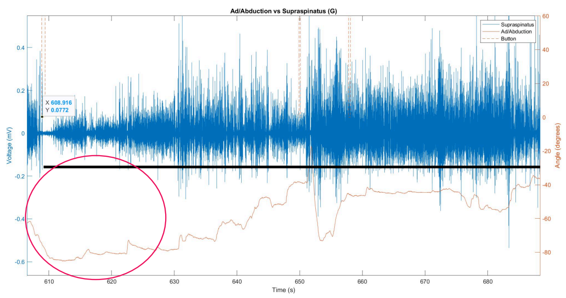


Figure 5.6l.2: Muscle activity supraspinatus with posture two circled.

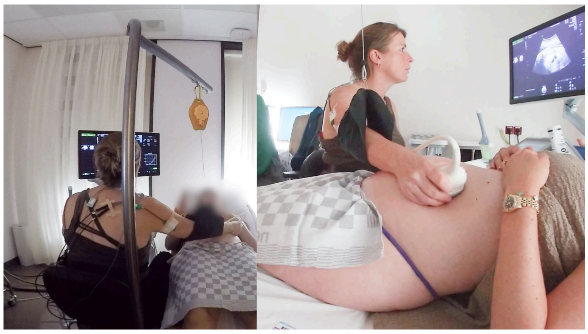


Figure 5.6m.2: Posture two.

3

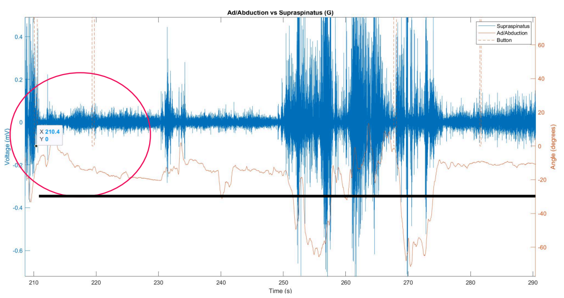


Figure 5.6l.3: Muscle activity supraspinatus with posture three circled.

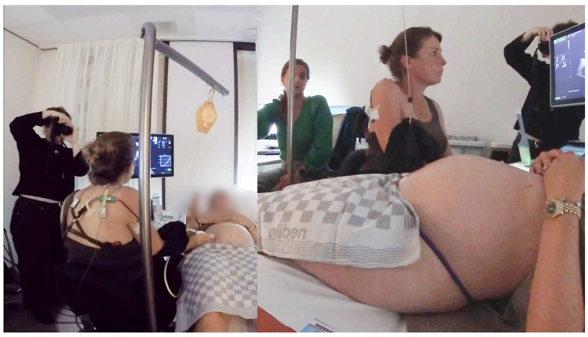


Figure 5.6m.3: Posture three with arm close by.

Trapezius
Figures 5.6n.1-3 show the activity of the trapezius and the abduction/adduction of the shoulder at the three extreme points (Figures 5.6.m.1-3).

In the first posture the activity is constant and on average. In the second posture, we see the same as in the first posture. The graphs again shows the correlation that with bigger abduction, the activity is a little less, but this is marginal. In the third position, the muscle activity is again average. Figure 5.6n.3 has the same big peaks at the end of the graph as 5.6l.3, These are caused by changing the position of the spring base.

1

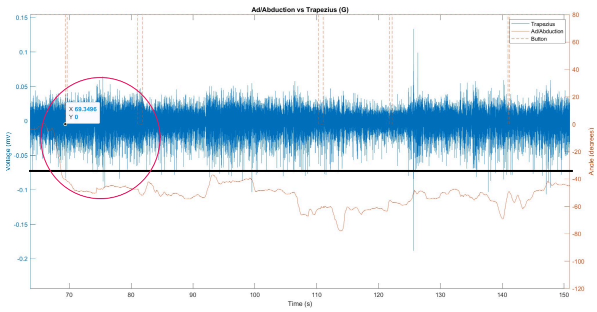


Figure 5.6n.1: Muscle activity trapezius in posture one.

2

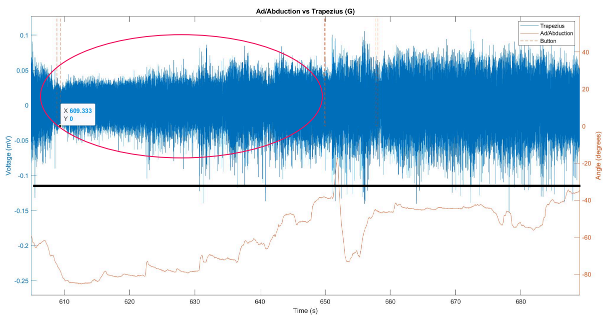


Figure 5.6n.2: Muscle activity trapezius in posture two.

3

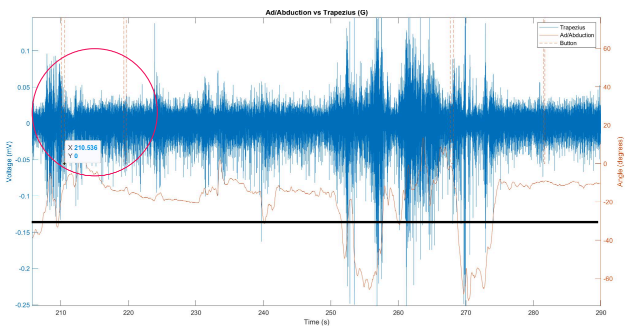


Figure 5.6n.3: Muscle activity trapezius in posture three.

5.6.5 Pain moments at both departments

During both tests with Lofius, pain or other notable moment were captured. They are recorded below.

Paediatric department
No pain was mentioned during the test, only afterwards.
While in the LLD position, the participant noticed that the sling was slipping backwards. Lofius did not provide the necessary support at that moment. After adjusting, the support improved, but was still not optimal. This is because the sling does not work as well with the arm in a slanted position as it does with the arm in a horizontal position, as in the supine position. The moment of slipping and the adjusted position are shown in Figure 5.6o.

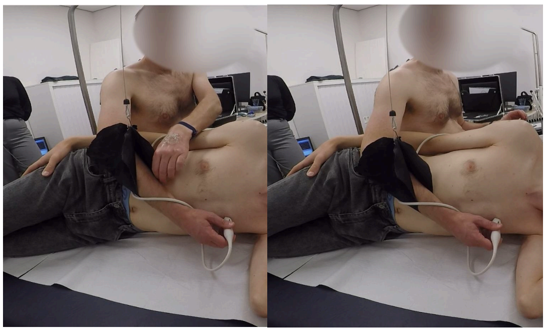


Figure 5.6o: Sling position before and after adjusting.

Gynaecology department
Thirteen moments were noted during the test, in addition to the 43 posture changes (see Appendix O). Of these, the participant reported pulling in four moments. These moments all described the same problem: the arm and sling should move with the user when performing the ultrasound. The user reported no instances of pain. It was mentioned that the support was nice in the neutral position, but outside of this, it was difficult because the user needed to pull harder on the sling to reach the position. The positions can be seen in Figures 5.6p.

Postures A and B illustrate the moment when the lower abdomen needs to be accessed. As the spring was fixed in one position, the user had to pull harder to reach the lower part of the belly.

Postures C and D show the posture required to scan the left side of the belly close to the body. The participants mentioned the following: *"This position is always difficult because I have to turn my upper body towards the patient to reach it. But now I also need to pull down the sling. For this, I use the lower part of my upper arm muscles rather than the ones in my shoulder."*

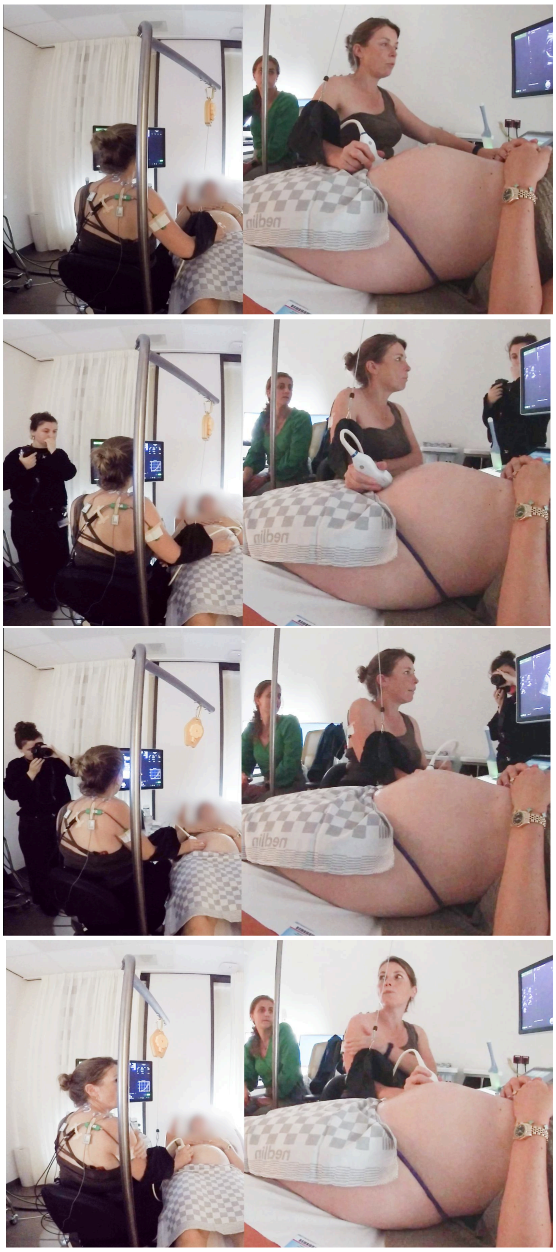


Figure 5.6p: Top to bottom: Postures A, B, C and D.

5.6.6 Comparison of EMGs with and without Lofius

To determine if the use of Lofius caused less muscle activity a comparison has been made between the two EMG tests.

Method

In order to accurately compare the tests without Lofius (the status quo, which we will call "test") and the ones with Lofius (the "retest"), we again look at the EMG data gathered. First, we rectify the signal in order to get the absolute values. Then, a bandpass filter is run over the signal, in order to get rid of measurement bias, noise and artefacts. Thereby, we isolate the signals within the muscle-activity frequencies. These steps are not strictly necessary, but they make the visualisation a bit cleaner.

The key of the analysis is finding the Root Mean Square (RMS) value. This is a proper representation of the power (muscle activity) over a longer period of time, as opposed to the muscle voltage that is point-based. The RMS was calculated in a moving window of 100 ms. This means that for every time point, the voltages of 50 ms before and after that point are squared, averaged and then rooted. This inherently compensates for the fluctuating nature of the EMG measurement. Excessive peaks where clipped for a cleaner analysis and visuals.

As was mentioned in Chapter 2, the location and connection of the EMG sensor tags, as well as numerous other factors, strongly influence the EMG measurement. Therefore, we cannot simply compare the RMS of the test to that of the retest: the tags have been removed and replaced. To resolve this, we normalise each measurement with the average RMS of the 'rest'-EMG that was conducted before each test. It is assumed that these measurements are the same, as rest *is* reproducible. Normalisation was performed by dividing the RMS values of the test and retest with the average rest RMS. Then, they were plotted in order to visually compare them.

Because of the different duration of the measurements, and also the different durations of the parts therein, it is not realistically possible to compare positions one-on-one. Therefore, we cannot simply translate the differences into a single number or value.

Results paediatric department - LLD

As mentioned in the method section it is not possible to compare the results of the two test one-on-one but it is possible to look at the overall difference of the two plots. Figure 5.6q shows the comparison between the muscle activity of the supraspinatus in the LLD part of the examination. As the two tests did not completely follow the same sequence it is not possible to compare the peaks. But overall it can be concluded that the retest in red shows less muscle activity compared to the first test without Lofius.

The activity of the trapezius was not as different between the postures, as was already found in both EMG tests. Figure 5.6r shows the comparison between the two tests of the trapezius activity. The retest activity seems to lay lower than the test, but for the larger part, matches it.

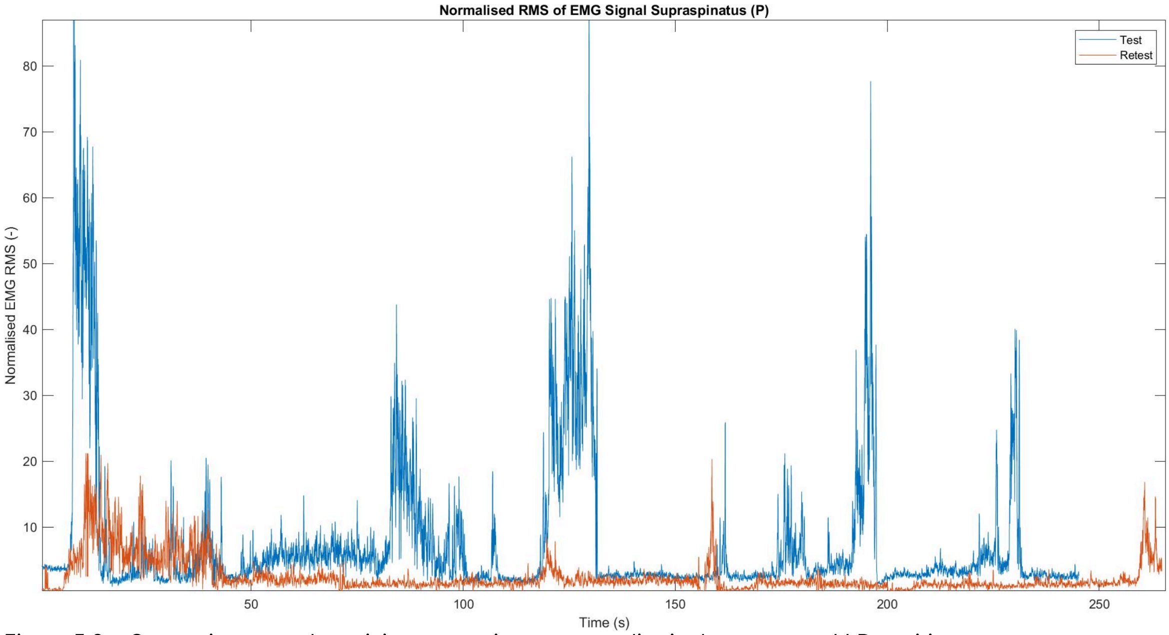


Figure 5.6q: Comparison muscle activity supraspinatus at paediatric department - LLD position.

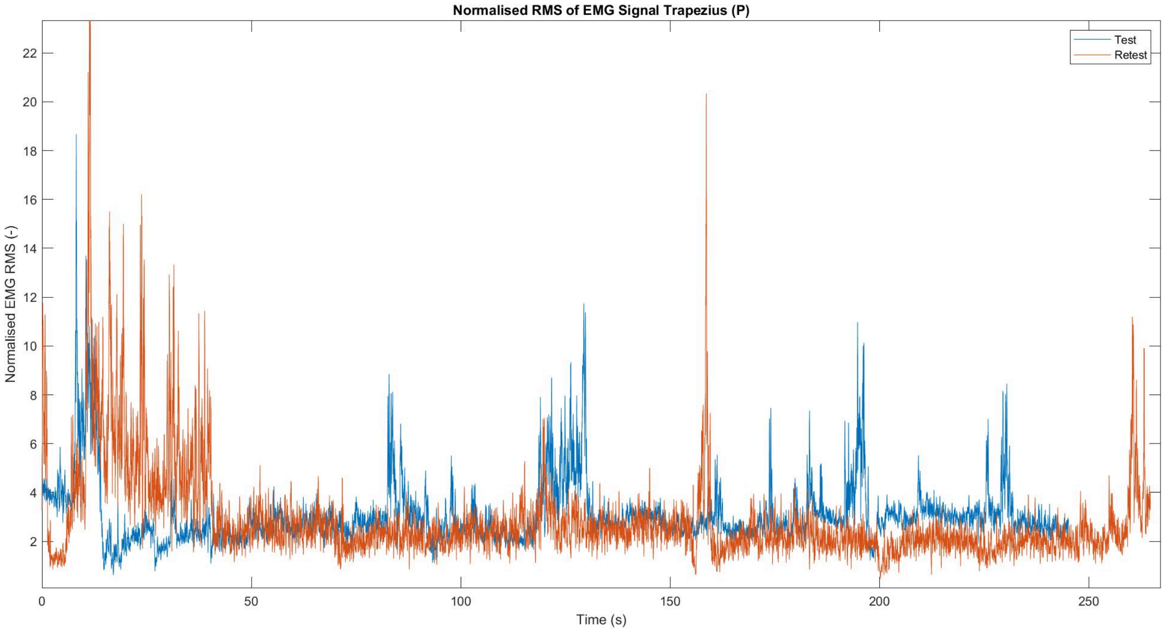


Figure 5.6r: Comparison muscle activity trapezius at paediatric department - LLD position.

Results paediatric department - Supine

For the supine position of the paediatric examination, we see something different than before. Figure 5.6s shows the comparison between the muscle activity of the supraspinatus in the LLD part of the examination. The retest in red shows rougly a factor 1- less muscle activity compared to the first test without Lofius. This is a lot more than in the LLD part, and also more than we will see in the gynaecological test.

The activity of the trapezius is also less in the retest as compared to the test, as shown in Figure 5.6t. The graph of the test with Lofius is consequently lower than without Lofius, indicating less muscle activity in the whole shoulder area. This is in line with the results of the supine part of the EMG test in Paragraph 5.6.3, and will be discussed in Paragraph 5.6.7.

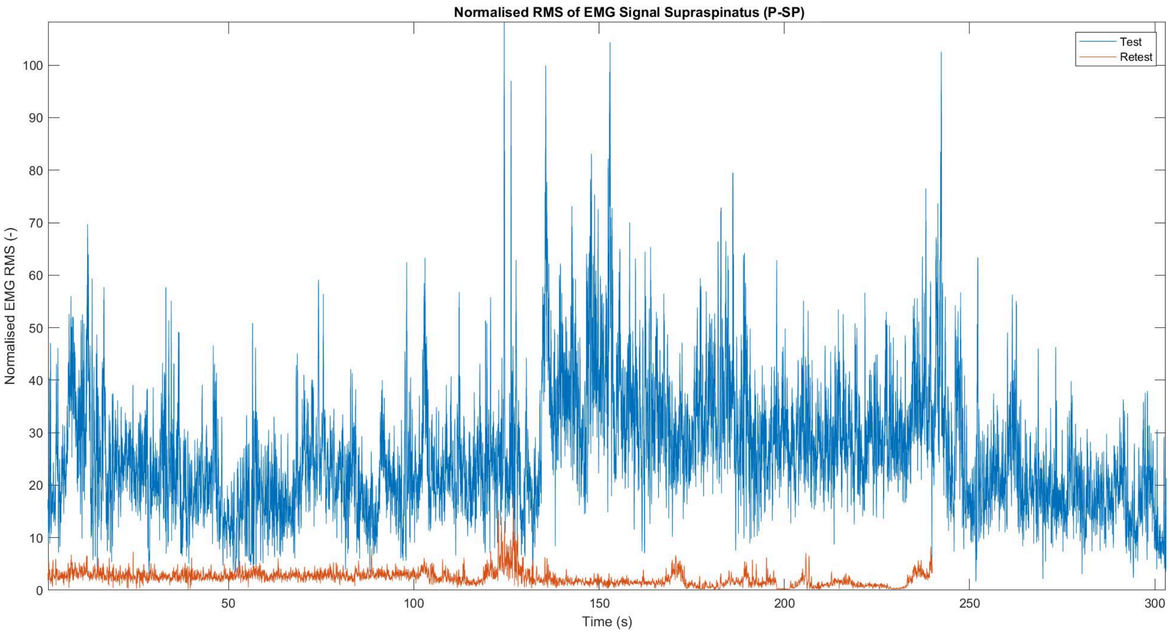


Figure 5.6s: Comparison muscle activity supraspinatus at paediatric department - Supine position.

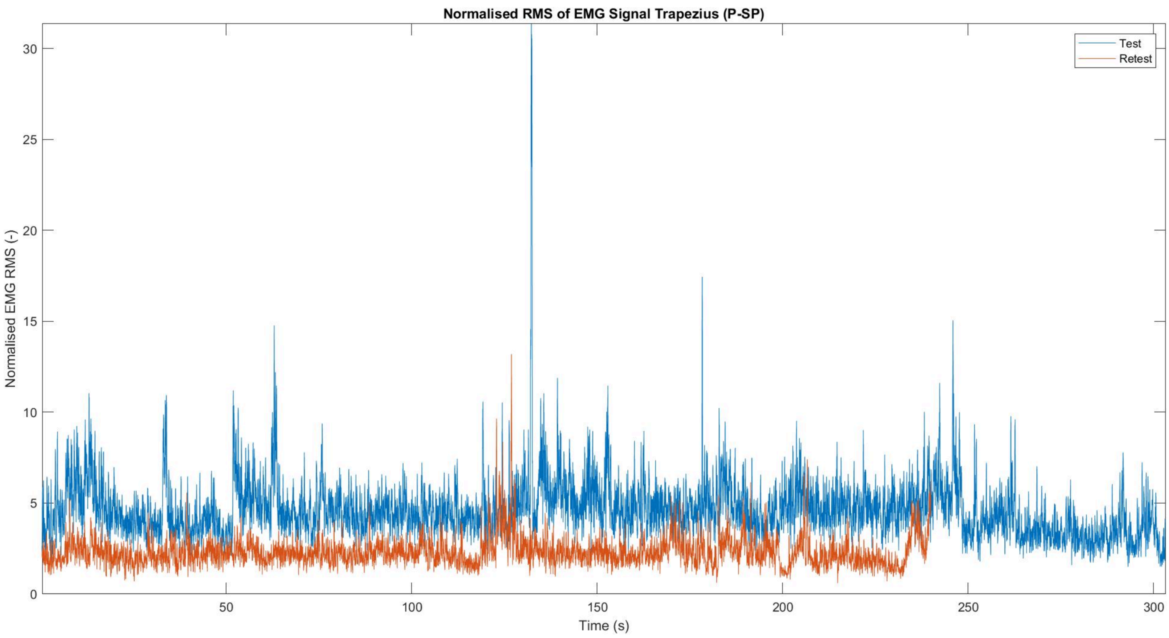


Figure 5.6t: Comparison muscle activity trapezius at paediatric department - Supine position.

Results gynaecology department

Figure 5.6u shows the comparison between the muscle activity of the supraspinatus. As the two tests did not follow the same sequence (every procedure is different because of the baby's position), it is not possible to compare the peaks. But overall, it can be concluded that the retest in red shows less muscle activity compared to the first test without Lofius.

Also at the gynaecology department, it was found in both EMG tests that the activity of the trapezius was not too different between the postures. Figure 5.6v shows the comparison between the two tests of the trapezius activity. This shows matching graphs, indicating no difference in muscle activity.

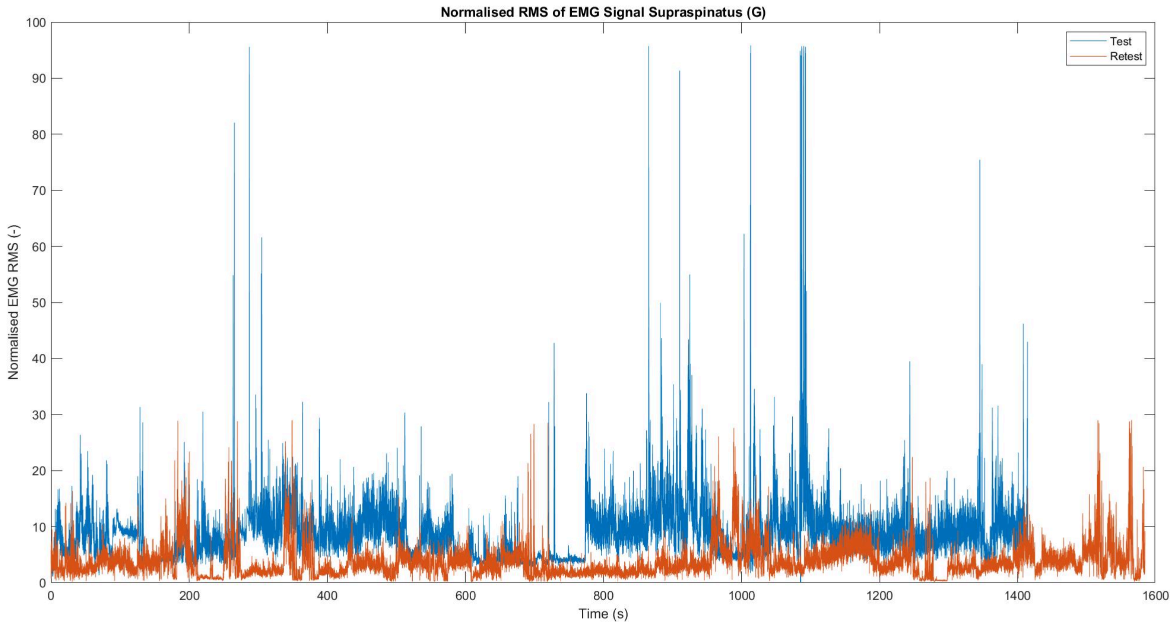


Figure 5.6u: Comparison muscle activity supraspinatus at gynaecology department

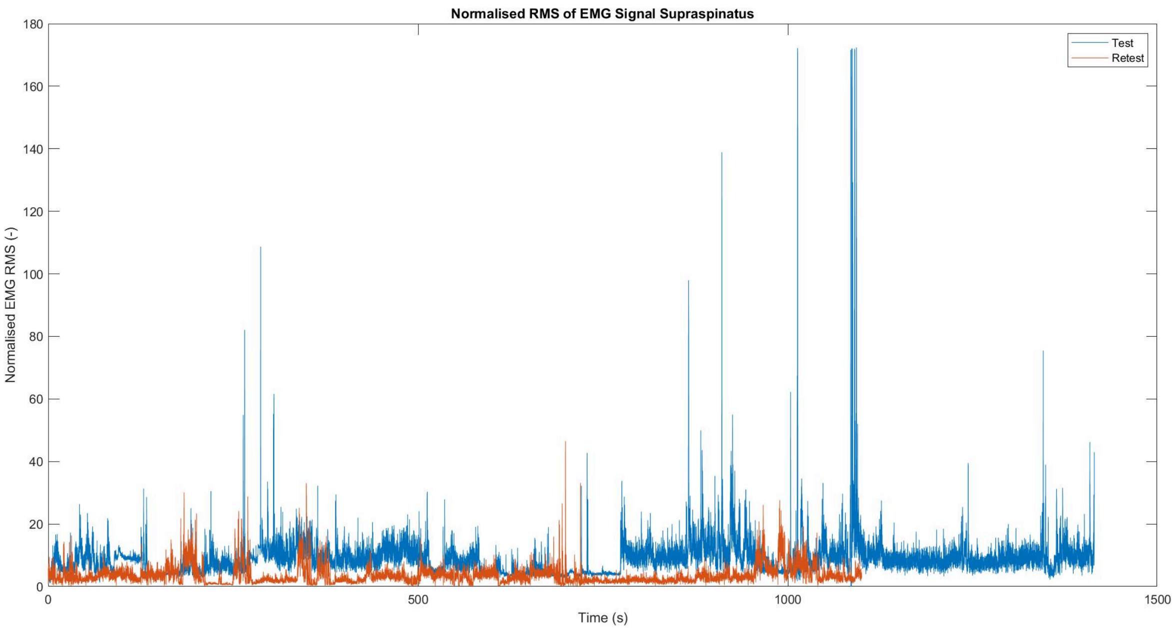


Figure 5.6v: Comparison muscle activity trapezius at gynecology department.

5.4.7 Discussion and Conclusion

This study evaluated muscle activity and arm abduction during ultrasound procedures in the paediatric and gynaecology departments. In the paediatric department, measurements were taken in both LLD and supine postures, while for the gynaecology department, the test involved dynamic postures. The three representative RULA positions were again used to analyse the EMG data of the gynaecology department.

Arm Abduction
Abduction beyond 30 degrees, a known WRMD risk, was common in the paediatric LLD position (72% of the time), driven by the need to reach over the patient. In contrast, the supine position resulted in only 5% abduction above 30 degrees, demonstrating a significant ergonomic improvement. At the gynaecology department, abduction exceeded 30° for 57% of the time, particularly in posture two. Posture three, with the arm close to the torso, involved no abduction.

Muscle Activity
Supraspinatus activity correlated closely with abduction and arm support. In paediatrics, examination in the LLD position showed consistently high activity, especially during arm lifting and transitions. Gynaecology postures demonstrated moderate and stable activation, with posture three again producing the lowest activity, supporting the value of reduced arm elevation.

Trapezius activity remained relatively low and stable across both departments, with brief increases during repositioning. These findings suggest a secondary role for the trapezius compared to the supraspinatus for lifting the arm.

Discomfort and Support Issues
While no pain was reported, participants noted discomfort, particularly in the paediatric LLD position, where the sling occasionally slipped and failed to provide consistent support. In gynaecology, strain was noted during four specific moments involving repositioning and fixed support limitations, especially when scanning required torso rotation and arm extension.

These highlight the importance of the proposed tool, Lofius, to not only support the user but also adapt to user movement.

Comparative Analysis: Procedures With vs. Without Lofius
To further assess Lofius' ergonomic impact, EMG results were compared between procedures performed with and without the support tool. Although direct peak-to-peak comparisons were limited by variation in sequence and posture, the overall patterns in muscle activation provided meaningful insights.

In both departments, supraspinatus activity decreased noticeably during procedures using Lofius. In paediatrics, the EMG signal in the retest (with Lofius) consistently fell below the initial test (without Lofius), indicating reduced muscle effort. Similarly, at the gynaecology department, overall supraspinatus activity was lower in the retest, despite procedural variability. These reductions suggest a meaningful ergonomic benefit in terms of shoulder load.

Conversely, trapezius activity remained consistent across tests, indicating that this muscle may be affected less by Lofius support and less involved in the abduction of the arm than expected.

Paediatric - Supine test
As could be seen from Paragraphs 5.6.3 and 5.6.6, the supine part of the paediatric examination shows great differences between the test and retest. At least, the results of the retest are in accordance to each other: both the abduction (specifically, the part above 30 degrees) and muscle activity are lowered by a factor 10. This would plead for an amazing advantage when using Lofius. However, it could also be an error in our test. Lastly, it could also be that the procedure was so different that it would accord for these differences. Then the question becomes: what was the influence of Lofius on this changed procedure, or was it accidental? And is it nicer for the sonographer to scan like this, i.e. is it reproducible? Further research, with subjective evaluation, is needed for this.

Limitations

Several limitations identified in the earlier test also apply to this analysis. The EMG setup focused solely on the supraspinatus and trapezius, excluding other muscles involved in arm abduction, such as the deltoid and serratus anterior. Minor inconsistencies in sensor placement and goniometer alignment may have impacted measurement accuracy. Additionally, because the test was conducted in a simulated environment rather than during real clinical procedures, the participant may have exerted less effort than under typical working conditions.

Next to this, in the gynaecology test, only three postures were analysed in depth, despite a greater number of posture changes being recorded, limiting the scope of detailed analysis.

In the second test with the use of Lofius, wrist flexor activity was not recorded, as the presence of EMG cables could have interfered with the use of Lofius. While this choice minimised obstruction, it also limited insight into wrist and forearm strain during the procedure.

Another constraint was the difficulty in replicating exact electrode placement across the different tests. Even minor variations in sticker location can lead to differing EMG readings, affecting the comparability of results. This issue is further compounded by the use of a different simulation patient in the gynaecology test, which may have introduced differences in posture and muscle activation due to the different position of the baby in the belly and the different size of the belly.

To account for these sources of variation, normalisation with the rest RMS is used. However, this is also not ideal, as differences in rest-EMGs because of incurred, latent muscle tension cannot be taken into account. However, it is assumed that the major part of the observed differences is due to the tags' location and sticking conditions, which we can cancel out by normalising with the rest-EMG.

Conclusion

Overall, the use of Lofius was associated with reduced supraspinatus activation, particularly in scenarios with abduction, pointing to potential benefits in minimizing shoulder strain. While trapezius involvement remained unchanged, the findings highlight the importance of effective and adaptive arm support in reducing muscular workload during ultrasound procedures. Future research with standardized protocols and larger participant groups is needed to confirm and expand on these findings.

5.7 Feasibility & Viability

5.7.1 Feasibility

Technical feasibility
Lofius is compatible with all class 4 ergonomic stools that RdGG has to offer as they all have diameter base of 50 mm. Because Lofius only needs the ergonomic stool to function, it can be used with all different kind of examination beds. Due to the compact design, it can be used in all ultrasounds rooms at the paediatric and gynaecology department. Next to this, for further implementation the spring base cover should be iterated to fit all standards of infection prevention.

One of the participants in the expert testing mentioned that patients are likely to grab something to pull themselves up. The arm is out of reach (shown in Figure 5.7a) so they can only hold the sling, which will not give support as the spring will stretch.
However, the risks must be taken into account that patients will grab the arm even when it is far out of reach. Using a Finite Element Method (FEM) analysis, the bending of Lofius is analysed for different weights to see what weights it can hold. Figure 5.7b shows the results of a maximum bending of 10 cm with 100 N (10 kg) at the end of the arm. When 350 N (35 kg) is applied the arm will bend 31 cm at the end. Appendix P shows all the different FEM results. A more realistic FEM analysis should be done to validate these results and to look into solution to minimize the bending.


Figure 5.7a: Reference of patient’s point of view.

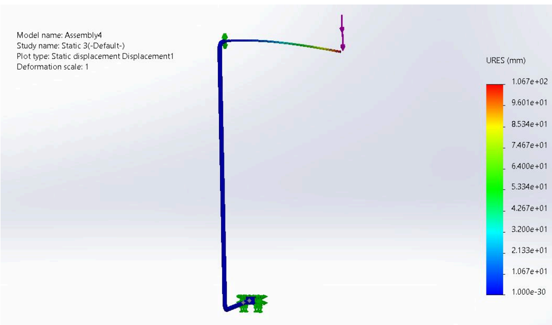


Figure 5.7b: Results FEM analysis Lofius.

Operational feasibility
Lofius fits smoothly into the daily routine of the sonographers at RdGG. At the paediatric department Lofius will be installed on the sonography stool that is placed in the ultrasound room by the doctor’s assistant from storage and also will be placed back in storage after the day. At the gynaecology department Lofius will be installed on two sonography stools and placed in both the ultrasound rooms and stay there. The doctor’s assistant will clean Lofius after a day of use.
The users adoption is difficult to estimate. It would be recommended to try out a few times to get the hang of it. Lofius is designed to take as little time as possible to setup making it easy to rotate between using it. Most of the time two stools are available in the room so switching is possible. Next to this it is important to spread awareness at the departments about WRMDs and how Lofius helps them. This could be done with a poster or info talks at the departments. The first time use of Lofius will be done with supervision of a HSE coordinator. Afterwards individual use is fine.

Requirements Validation
A list or requirements was made to make the design of Lofius fit it’s context. Appendix Q shows the list with a brief explanation on how it is met. Almost all requirements have been met. As already discussed is the 350 N force resistance not met. Further research needs to show if this force resistance is necessary or what features can be added to withstand these forces.

Nex to this the heat resistance of the cover module should be further researched as now it is made out of PLA. Also in influence of the heat on the spring base is not clear. Lastly, the cover should be iterated to make cleanability easier and allow less dust to enter the cover.

Economic Feasibility
The cost of one Lofius will depend on where it is produced. For the first period after this project three prototypes should be made (two for gynaecology, one for paediatric department) to start the clinical testing.
The price of this prototype would be 186 euros when produced in-house. The departments should find room in their budget which is not public available. When Lofius meet it's expectations a company can be approached for upscaling to be used in multiple hospitals.

Legal and Regulatory Feasibility
As stated before Lofius does not need to comply to the MDR because the product is used for prevention of WRMDs. When the product is only used and produced inside of the hospital it also does not have to have a CE certification according to Liaison Officer Timo Oosterveer who is writing a protocol about in-house development.
It is important that before clinical testing infection prevention and a clinical physician have looked at the design.

5.7.2 Viability

Clinical Viability
As the second EMG test proves that the muscle activity of supraspinatus is less with the use of Lofius we are a step closer at the prevention of WRMDs in the shoulder due to sonography. With clinical testing over a longer period the effectives can be further tested.
The use of Lofius will be relevant until the entire setup of the ultrasound equipment will be changed to make it easier to perform left and right handed sonography.

For scalability to other departments were sonography is also used, clinical testing should also be done to determine if Lofius fit's the procedure. During observation at the Radiology and Vascular department the same WRMDs problem were mentioned.

Financially viability
The minimum payroll as gynaecologist based on an 45 hour contract is gross monthly salary of 8192 euros. This translates to 378,27 each day. With a gynaecologist not able to work the hospital looses roughly 380 euros each day.
Next to this temporary replacement needs to be hired adding to the absence cost

With Lofius costing 186 euros when it is produced in-house it could be a wise investment. Next to costs, a satisfied employee will enhance the care of the patient which is priceless.

6 Discussion and Conclusion

This final chapter brings the graduation project to a close by reflecting on the key findings and acknowledging its limitations. It then offers recommendations for the RdGG to support the continuation of the project. The chapter concludes with a summary of the overall outcomes and a personal reflection, highlighting the learning objectives and insights gained throughout the project.

6.1 Discussion

The aim of this graduation project was to develop a supporting tool to prevent work-related musculoskeletal disorders (WRMDs) caused by ultrasound practice. The result was Lofius, a tool designed to reduce WRMDs in the shoulder area. Surface EMG testing was conducted to determine whether muscle activity decreased when using Lofius. The results showed a correlation between using Lofius and reduced supraspinatus muscle activity. This is a promising result with respect to reducing strain in the shoulder muscles. The design has been developed to enable use in paediatric and gynaecology departments, with the prospect of use in other departments. Also, the design considers a variety of patients, making it usable from prenatal care to adulthood.

Given these promising initial results, it is important to delve deeper into what they reveal about the tool's effectiveness and its implications. In line with the hypothesis that a supporting tool will significant reduce the supraspinatus stiffness, the EMG results show a relief of muscle strain. Especially long ultrasound duration, as performed in the gynaecology department, can have a major effect on the muscle strain. This effect was supported by Wong et al. (2021), who demonstrated that reduced muscle activity helps minimize muscle fatigue.

The abduction of the arm muscles also contributes to strain. Goniometer data from the EMG test showed that the arm is abducted more than 30 degrees over 50% of the time, known to accelerate the onset of fatigue. Lofius can provide critical support here, as Wong et al. (2021) also showed a significant reduction in supraspinatus stiffness when the scanning arm is supported across all abduction angles tested.

Notably, the amount of time spent in >30 degree abduction differed for the test and retest in the paediatric department. We saw a shift from 94 to 72% and 50 to 5%. This is likely to be a measurement error, as the user performed the same examination.

It is important to look at the effectiveness but also the effect it has on the bigger picture. The struggle with WRMDs is not only a problem at RdGG; many sonographers experience WRMDs, resulting in absenteeism of up to 20% for extended periods or even permanently.

Given the ongoing shortages in the Dutch healthcare sector and the increasing number of ultrasounds being performed, it is crucial to ensure that sonographers can perform their work safely and sustainably. In both paediatric and gynaecology departments, the primary burden lies in the shoulder region. Lofius addresses this issue effectively by specifically targeting and relieving the supraspinatus, helping to reduce physical strain and potentially improve workforce retention and well-being.

Limitations

While this study provides valuable insights into WRMDs and the effects of using Lofius, it is important to acknowledge several limitations in order to interpret the findings accurately. Firstly, testing of Lofius was based on only one complete ultrasound performance in both the paediatric and gynaecology departments. Longer clinical testing, involving multiple subjects from each department, over several weeks is necessary to determine whether Lofius is working as expected. This will enhance the generalizability of the findings.

Furthermore, the project focused only on the paediatric and gynaecology departments. Therefore, if the hospital wants to expand the use of Lofius to other departments, testing must be conducted to determine its suitability for these departments' procedures.

As discussed in Chapter 3, future support during ultrasound should also assist with providing force. While Lofius cannot assist with this, it is possible that force assistance could be combined with Lofius, together tackling the two major challenges causing WRMDs.

Another limitation could be the way the EMG test was set up. The two tests were carried out months apart. Ideally, the sensors should be in the same position for tests with and without Lofius. However, this would mean carrying out the two tests on the same day, which is logistically challenging and the muscle would already be strained by the time the second test was carried out, which would skew the results.

The most effective approach was to normalise the data using the EMG data in rest. However, there is still a bias due to differences in muscle strain, the time of day the test was performed, sensor positioning and the order of steps in the procedure.

Lastly, the EMG test was performed with the spring base hooked onto the arm. After this test, the design was changed to a sliding system. This new system has been briefly tried out in both departments, but a full test is necessary to validate the design change.

Recommendations
Before clinical testing, the design of the spring cover should be integrated to fit all the standards for infection prevention. This includes limiting the possibility of dust going in at the top and bottom of the cover. Next to this, the arm still bends a little when Lofius is in use. In the ideal situation the arm should stay horizontal to enhance the sliding mechanism. This could be done by increasing the tube size or adding corner reinforcement.

During clinical testing a few parts of the design should be tested. First of all if the range in resistance weight is wide enough for p20-p80 or that they would need more or less resistance. Secondly it should be tested if the movement range from the sliding system and the hinge is enough. Lastly, the muscle strain should be reported over a longer period of time to see if there are improvements.

For RdGG a few possibilties are highlighted to tackle this next phase. There are three possible routes they can take to get Lofius into practice. The first one would be to hire a graduation student from Industrial Design Engineering, Clinical Technology or Biomedical Engineering to set up the clinical testing of Lofius and do some small alteration to the design. The second route would be to continue with the current project team to setup the testing and scale up to three prototypes that can be used in RdGG. The last route would be to find a company in the medical equipment sector that want to further develop this in collaboration with RdGG.

For now, we have realised Remus by means of Lofius. For the long term solution, Romulus, we should look beyond supporting the ultrasound user. Different methods of applying force, or assisting in applying force, should be explored and evaluated. We have found that the examination room offers limits more than it enables, which is a pity. However, we should keep discovering new ways and possibilities, as to not forsake our goals of eliminating WRMDs for sonographers. Lofius is just a starting point.

6.2 Conclusion

Research shows that almost all sonographers experience WRMDs (Zangiabadi et al., 2024), which significantly impact their ability to perform ultrasounds. By analysing the context and causes of WRMDs in both the paediatric and gynaecology departments, this thesis demonstrated how Lofius could contribute to prevention of WRMDs in the shoulder area. The study addressed three research questions concerning the key risk factors and differences between the two departments, and set out design requirements for Lofius.

Key risk factors
The most significant risk factor is shoulder abduction exceeding 30 degrees, which occurs almost 50% of the time in both departments. This accelerates the onset of fatigue in the supraspinatus. Another risk factor is the force that needs to be applied to corpulent patients. Lastly, the sonographer's posture should be as natural as possible, but the current setup does not allow this.

Key differences
The main difference between the paediatric and gynaecology departments is the type and frequency of movements required to perform an ultrasound. In the paediatric department, the probe is placed in a static and predictable position. In the gynaecology department, however, the entire lower abdomen is covered, and the position often changes. Additionally, in the paediatric department, the patient lies on their left side and back, whereas in the gynaecology department, the patient usually lies on her back. Therefore, flexibility of the Lofius is important in both departments.

Design requirements
A full list of requirements was compiled based on the small and large demands identified during observations and testing. These include topics such as movement fields, safety and hygiene.

The three research questions led to the development of Lofius, an ergonomic support designed to prevent shoulder injuries caused by ultrasound practice. The tool supports the weight of the arm, resulting in less muscle strain in the shoulder. A hinge and sliding system enable micro and macro movements, providing flexibility in how Lofius can be used. This means that the user is not restricted.
Lofius is designed for the context, in the context, with the help of the user.

6.3 Personal Reflection

Over the past six months I have had the opportunity to learn about sonography and experience working in a hospital. I was welcomed with open arms and was allowed to ask all the questions that I wanted.

My goal of this graduation project was to create a prototype and test it in the context. Next to this, I wanted to use qualitative research to validate my design. With pride I can say that these ambitions were completed and that I enjoyed every moment of it. I would like to take an moment to look back and reflect on my learnings.

Creating together with the user
Throughout my whole education I was eager to find the user of the product and design together with them. Especially in the medical field this is crucial because I don't have a medical background so I need to learn from the user and discover the context to know where to design for. I also noticed that because I come outside of the medical field I have a fresh point of view. I got noted for me keeping asking *why*? and challenging how things are done currently in the hospital.

I enjoyed sharing my findings with different stakeholders and hearing their personal experiences. It is good to see the bigger picture and align different views. I would love to continue doing this in my professional career.

Project management
One of the lessons I learned is to balance my time better between all the different parts of such a big project. In the beginning I wanted to learn in depth about the core problems of the case. I think if I started sooner on the prototypes I would not have struggled at the end of the project to get everything done in time. I am proud of my project management on planning the observations and tests way in advance. By keeping everyone informed about my wishes and planning in dates to tests as soon as possible, I was able to collaborate with a lot of healthcare professionals. And this can be a challenges as they have a busy schedule.

Final result
I am happy that Lofius was well received in RdGG. Visiting LUMC and Erasmus MC also gave me a better understanding of the scale of the problem and that Lofius is wanted beyond RdGG.

During the prototyping phase, I learnt a lot about new production techniques, such as lathing and welding. One of the most important lessons is to not try to do everything yourself, but to let other people help you. With the help of the PMB, I became familiar with these production methods, and I definitely want to learn how to do them myself in future.

Overall, I discovered that my core driver in design is working together with users in the medical field. In addition, I would love to continue working and learning more about ergonomics in the medical field.

Thank you very much for reading my report on WRMDs due to ultrasound performance. If you have any question or would like to discuss the project further, please do not hesitate to reach out!

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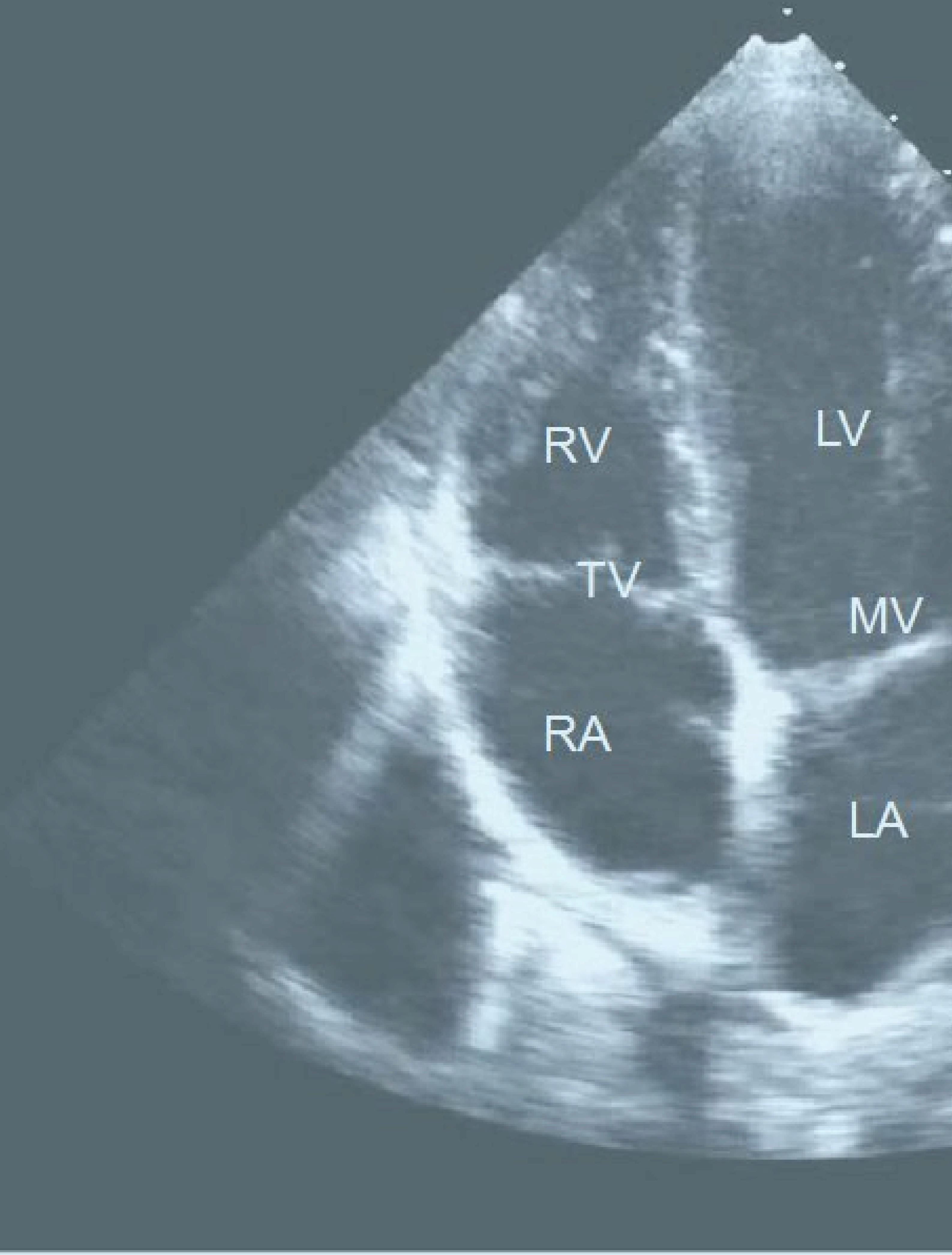
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