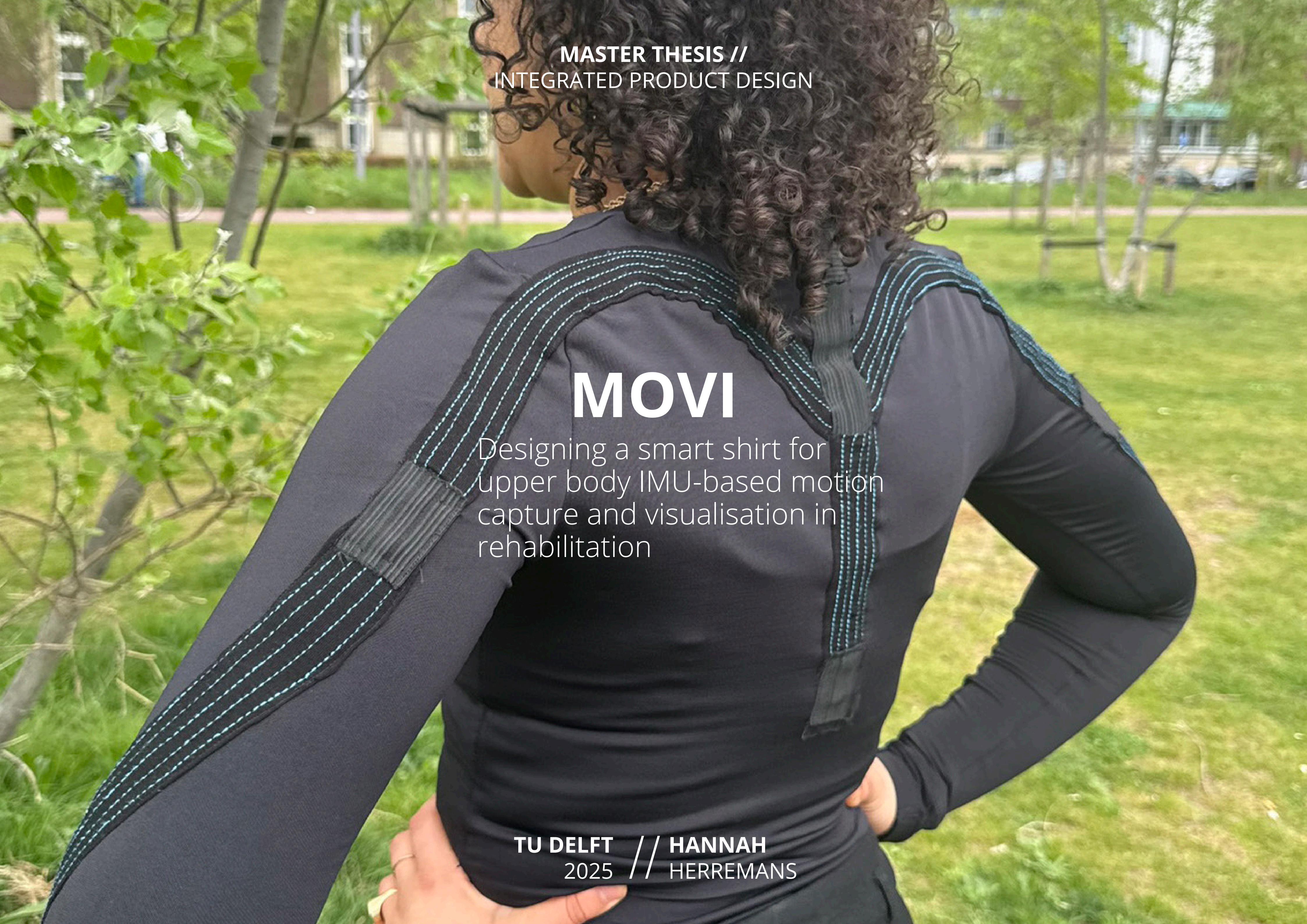

MASTER THESIS //
INTEGRATED PRODUCT DESIGN

MOVI

Designing a smart shirt for upper body IMU-based motion capture and visualisation in rehabilitation

TU DELFT // **HANNAH**
2025 // HERREMANS

Author
Hannah Herremans

Master thesis
Delft University of Technology
Faculty of Industrial Design Engineering
MSc. Integrated Product Design

Graduation Committee
Kaspar Jansen
Adrie Kooijman

Preface

Dear reader,

This report is the result of the last half year working on my graduation project. I have really enjoyed learning more about smart textiles, electronics and the rehabilitation sector, and above all bringing everything together in a working smart shirt.

First I want to thank Kaspar and Adrie for their time, helpful feedback and valuable discussions throughout the project.

A big thank you to everyone who has been involved in any way over the past few months. From the experts who shared their knowledge of the rehabilitation sector to the people at the Applied Labs who were always willing to help me. Lastly, I want to thank my friends, family, and the participants for their valuable insights, willingness to test, discuss, and support the project. Your help and support made this project come to life.

Enjoy!

Hannah

Summary

Background
One in three people requires rehabilitation, with the majority (90%) undergoing treatment at home. However, around 50% of patients do not fully adhere to their rehabilitation plans. IMU-based motion capture can assist both patients and rehabilitation specialists by addressing common challenges such as lack of motivation, time constraints, and incorrect execution of exercises. Integrating a visualisation tool into a smart garment using smart textile principles can offer an effective solution to these problems.

Project goal
The goal of this project was to create a proof of concept for an accessible smart shirt that integrates IMUs to capture and visualise upper-body movements for physical rehabilitation. The focus was on seamless integration, real-time motion visualisation, and aligning the design with patient needs.

Method
To ensure the concept aligned with the rehabilitation context and user needs, the project involved several key activities: desk research, expert interviews, benchmarking existing smart shirts, and prototyping. Insights were gathered from two rehabilitation doctors and two physiotherapists to understand rehabilitation practices and the needs of both patients and specialists. A benchmark of existing IMU-based smart garments helped identify ideas and challenges that needed addressing. A rehabilitation journey was developed to define the context, and a function diagram along with a list of requirements outlined the design criteria.

Prototype Development
The prototype development was divided into sections: motion capture visualisation, IMU integration, upper back design, wiring with conductive thread, and aesthetics. The motion capture visualisation focused on the electronics setup, rotational data gathering, and the use of OpenSense or Blender for visualisation. IMU integration addressed the placement and stability of the IMUs on the arms and their integration into the shirt. The upper back design explored the placement of electronics and the main node. Wiring with elastic thread focused on the conductive thread's placement and sensor connections. These individual concepts were combined into the final design.

Results
Movi is the working prototype resulting from this project. It features five BNO055 IMUs, a TCA multiplexer, and a Xiao Seeeduino wired with conductive thread integrated in elastic for seamless integration. The system provides real-time movement visualisation through Blender. The shirt is designed with a snug fit, using a sturdy sports shirt as the base, and is costs 220 euro for the materials. It is designed for easy separation of electronics and textiles at the end of life.

To evaluate Movi a performance and user test were executed. The visualisation is clear, stable, and offers a 0.23-second delay. While the precision can be improved with calibration, a method has been proposed that patients can perform themselves. Feedback from users indicated that the shirt is comfortable and easy to wear, with a good fit for women (sizes S and M) and a slightly tighter fit for men.

Conclusion
Movi demonstrates the feasibility of using IMU-based motion capture garments for real-time visualisation within the rehabilitation sector. It offers a more affordable and integrated solution compared to existing systems. The smart shirt allows patients to use it independently during exercises, improving their rehabilitation process at home. The patient gets visual feedback in real-time. Movi can be further developed into various applications, such as motivation tools, gaming, exercise guidance, progress tracking, and discussion tools for rehabilitation specialists, ultimately enhancing both the patient experience and the specialist's ability to track progress remotely.

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PHASE 0

Project outline

This first phase introduces the context of the master thesis by briefly outlining the rehabilitation sector, the use of motion capture, and the related challenges. It also explains the aim of the design project and the approach taken. The full project brief is provided in Appendix A.

This phase entails the following chapters:

Figure 1. *Movement of the leg during exercise*

1. Project introduction

This chapter provides an overview of the graduation project, outlining the key stakeholders, the challenges addressed, and the project's main objectives.

1.1. Project introduction

Physical rehabilitation plays a critical role in the recovery process for individuals with various health conditions, injuries, and chronic diseases. The increasing global prevalence of chronic diseases and an aging population has led to a growing demand for effective rehabilitation services (World Health Organization, 2020). According to the WHO's Rehabilitation 2030: A Call for Action, one in three people worldwide could benefit from rehabilitation, yet many face barriers to access (World Health Organization, 2020). This gap highlights the urgent need for innovative and scalable solutions to make rehabilitation more accessible, efficient, and cost-effective.

Traditionally, rehabilitation has relied on in-clinic interventions from trained healthcare professionals, such as physiotherapists and rehabilitation doctors. While these methods remain essential, they often involve time-intensive, labour-intensive processes that do not provide continuous monitoring of patient progress (Cieza et al., 2020). Additionally, patients frequently experience difficulties in executing rehabilitation exercises correctly when at home and in finding motivation and time to follow the physical therapy schedule. This impedes with efficient recovery and extend rehabilitation time lines (Argent et al., 2018).

The integration of motion capture garments into rehabilitation practices presents a promising approach to address these problems. Such garments enable real-time monitoring and feedback to patients on their movements during exercises. In particular, smart garments incorporating Inertial Measurement Unit (IMU) sensors are promising (Yin & Sun, 2025). This technology allows for movement tracking at any location without the need for extensive technical expertise, providing both patients and healthcare providers with valuable feedback. Applying smart textile techniques in the shirt could potentially improve the comfort of the shirt.

The primary goal of this project is to develop a proof-of-concept for an accessible smart shirt that integrates IMU sensors seamlessly into a garment to capture and visualise upper body movements for use in physical rehabilitation. This should be a practical, user-friendly solution that bridges the gap between research and a real-world application. It builds partly upon the work of Alamel et al. (2024), who developed a prototype of an IMU-based motion capture smart shirt for home-based physiotherapy with a focus on accessibility. However, their motion capture system encountered functional limitations, this project seeks to address these problems and improve upon.

1.2. Stakeholders

The main stakeholders of this project are the patient, the rehabilitation specialists, the client and myself, as a graduate student (Figure 2).

Patient
The patient is the primary user of the smart shirt. They want to recover as quickly as possible and face various challenges during rehabilitation. The smart shirt would help support their recovery process, and should match the patient's needs.

Rehabilitation physiotherapist
The rehabilitation physiotherapist guides patients through their rehabilitation process. They would benefit from tools that help patients with their daily exercises and progress.

Rehabilitation doctor
The rehabilitation doctor diagnoses the patient's condition and develops the rehabilitation plan. They would benefit from additional tools that offer insight into home-based rehabilitation, improving diagnosis and monitoring.

Client . The client, Professor Dr. Ir. K.M.B. Jansen, is a leading expert in smart textiles. His guidance ensures the project meets academic and practical goals. The project is supported by Delft University of Technology, which provides the academic infrastructure.

Myself, as a graduate student. As both the graduate student and the designer, I aim to integrate my academic knowledge into practical applications within this project and show the knowledge and skills I acquired during my study.

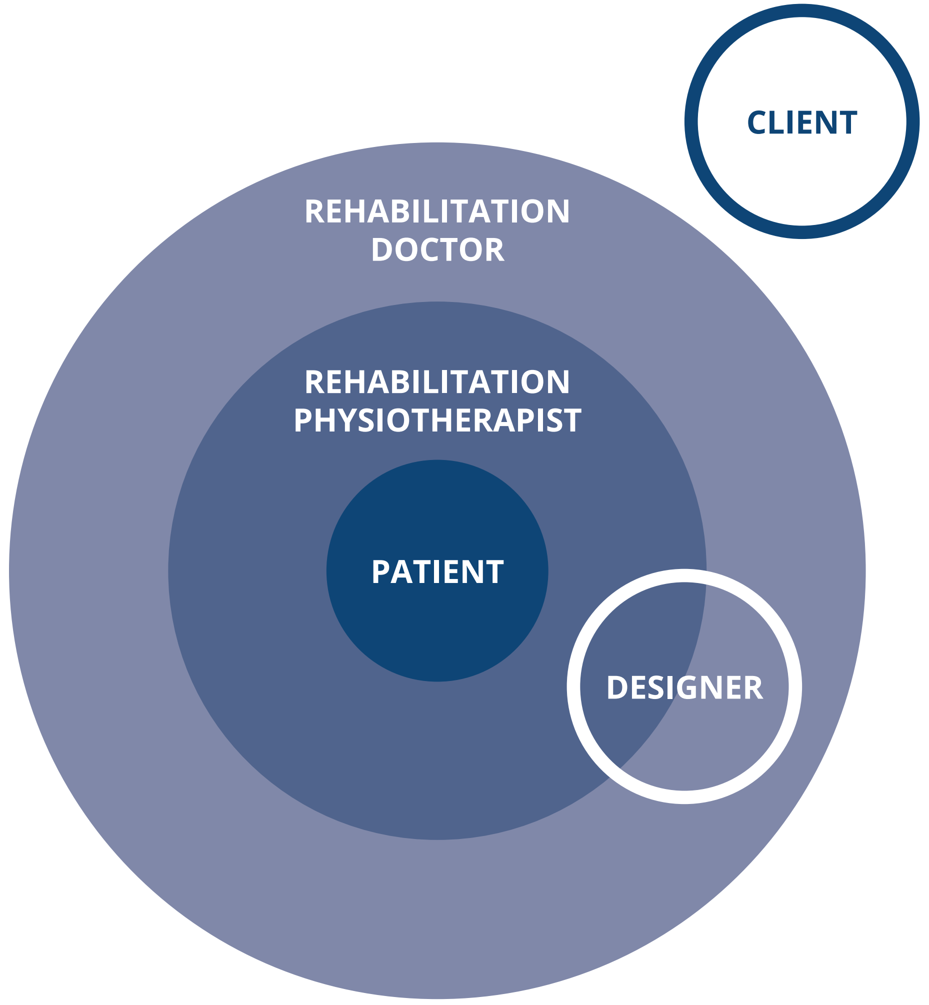


Figure 2. *Stakeholders map*

1.3. Problem definition

IMU-based wearable motion tracking systems have shown significant potential across various domains, including healthcare, the gaming industry, and sports performance (Ancans et al., 2021; Steijlen et al., 2021; Xsens, 2025). While both commercial solutions and research prototypes exist, the adoption of these systems within the rehabilitation sector remains limited due to several key challenges.

High costs
Commercial smart garments are often very expensive, with prices reaching multiple thousands of Euros per garment (Ancans et al., 2021). This substantial upfront investment creates a significant barrier for patients and rehabilitation clinics. As rehabilitation needs may last only a limited period of time, the perceived long-term value fails to justify the high upfront expense for patients. While hygiene and size of the shirt would force rehabilitation clinics to buy multiple shirts.

Complexity impeding independent use
Current IMU systems demand considerable technical expertise for proper and reliable use. Many systems consist of multiple sensors mounted on separate bands, each needing precise positioning to ensure accurate data collection (see Figure 4). This complex setup process is both time-consuming and error-prone, which makes these systems impractical, particularly in home environments where professional supervision is unavailable.

Inadequate human-centred design
Research into IMU-based motion capture garments frequently prioritises technical capabilities over human factors such as comfort. Bulky sensor can interfere with normal motion patterns and discourage consistent use. While smart textile technologies offer promising opportunities for seamless integration, this brings their own challenges, including concerns around durability, reliability and washability.

PROBLEM STATEMENT
IMU-based motion tracking systems remain underutilised in rehabilitation due to high costs, technical complexity, and poor user-centered design.

WHY IT MATTERS
Addressing these barriers is crucial as it could
- expand access to rehabilitation technology,
- enable patients to benefit from personalized rehabilitation programs,
- accelerate recovery times through consistent monitoring,
- and potentially reduce overall healthcare costs by shifting therapy from clinical settings to the home environment.

Figure 3. *Project problem statement*

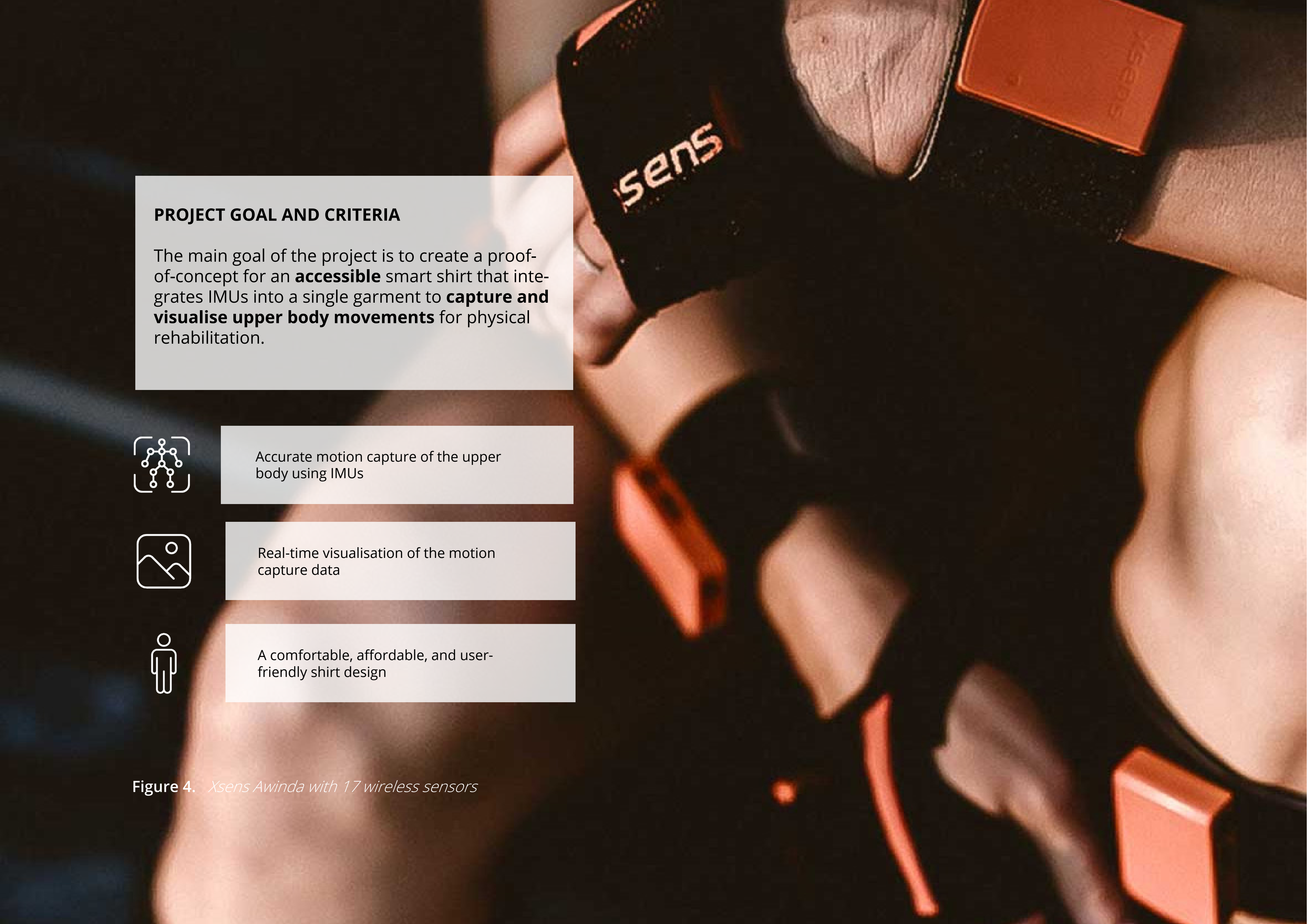


Figure 4. *Xsens Awinda with 17 wireless sensors*

1.4. Goals & criteria

The goal of the graduation project can be seen in Figure 4.

Scope
As the project takes place with in the master Integrated Product Design, it will focus on designing an integrated working prototype. The rehabilitation context and its users will be taken into account to make a meaningful and fitting product. Making the product market ready is out-of-scope. Also, the design of the visualisation is also out of scope.

Focus
The focus will be on creating a functional motion capture prototype. The project will explore possibilities to integrate electronics with textiles, specifically by exploring how to embed IMUs into a garment in a comfortable way.

Deliverable
The final deliverable is an integrated, working prototype capable of measuring and visualising upper body movements and recommendations for further developments. The report will provide context, ideas, insights and an evaluated final concept resulting from the activities conducted throughout this project.

Time frame and market
The project targets the smart textile and health sector in 2035. The year is distant enough to allow for technical development in smart textile research and smart wear acceptance in healthcare. Yet close enough to remain relevant, especially regarding the fast development.

Figure 5. *An ideation drawing of the smart shirt*

2. Project approach

This chapter explains the design approach used in the project. It outlines the overall process followed and the design methods applied.

2.1. Project outline

This project was conducted in 100 working days between November 2024 and May 2025. Work primarily took place at TU Delft, with biweekly feedback sessions held with my coaches. During the prototyping phase, a place in the Applied Labs was used, where the necessary tools and machines were available.

For the design approach of this project the double diamond design approach from the Delft Design Guide (Van Boeijen et al., 2020) was used as a basis. Within this graduation project the emphasis lays on the develop phase, and will therefore be highlighted in this report as well. Figure 6 outlines the different phases and the methods used.

While this report presents the process in linear order the actual approach was iterative. Research inspired ideas, ideas led to concepts, and concept development drove further research. For the sake of a coherent narrative, the insights and developments are presented in a linear and logical format, instead of chronological.

PHASE O - PROJECT OUTLINE
Phase O focused on initialising the project. During this phase, the aim of the project was defined, the project setup and planning was established with the supervisory team, and initial research was done.

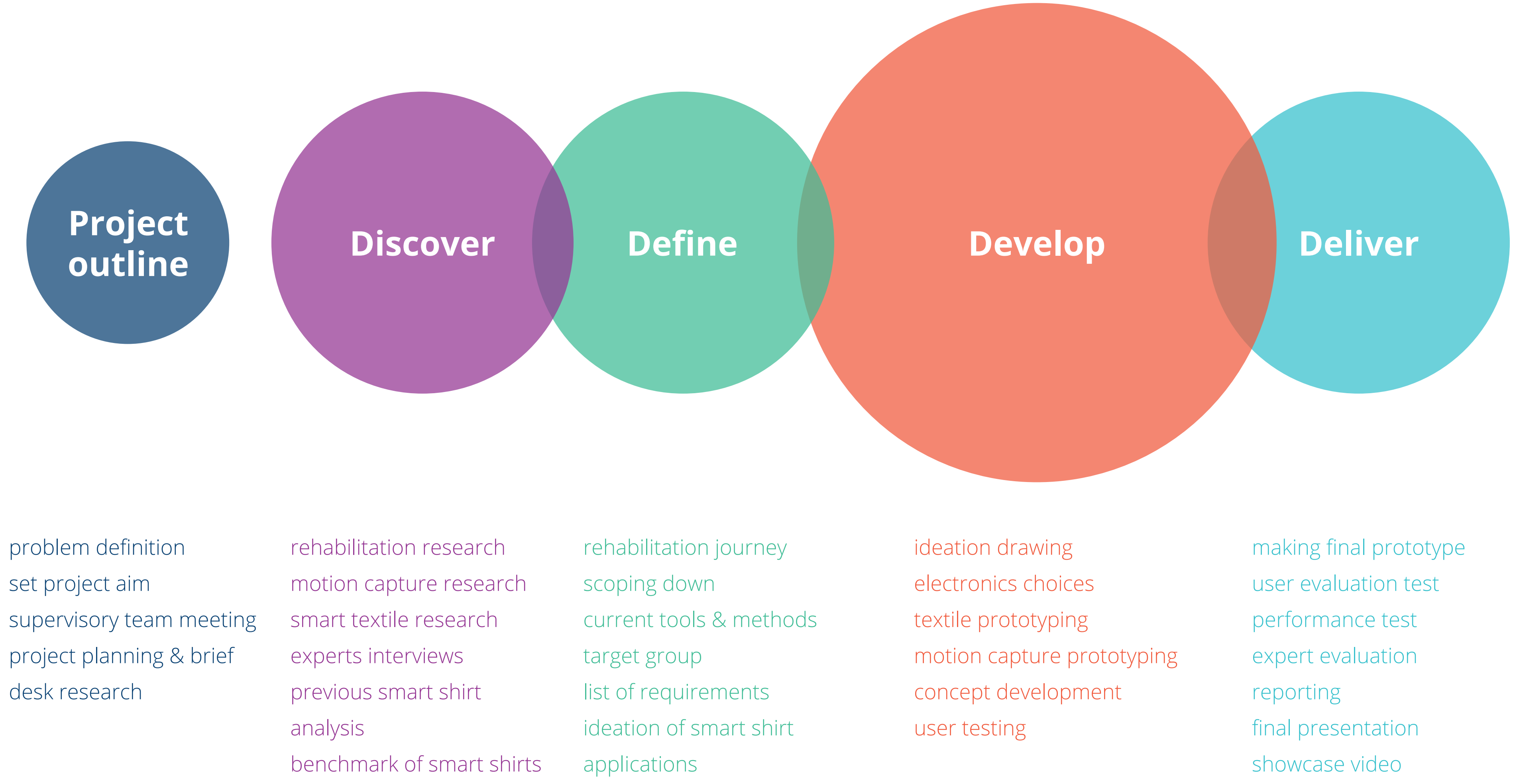
PHASE A - DISCOVER
The discover phase is about researching and exploring the problem space. Insights are gathered from literature research, users, stakeholders, and market trends to fully understand the challenge, opportunities and requirements.

PHASE B - DEFINE
In the define phase insights from the discover phase are analysed and synthesised to clearly define the design context and the core problem. The project's focus is narrowed down to a specific challenge, together with the associated requirements.

PHASE C - DEVELOP
In the develop phase ideas and solutions for the defined problems are generated and iteratively tested. Prototyping stands central within this project as a method to explore different design directions. The phase ends with defining the concept for the final prototype.

PHASE D - DELIVER
The final phase involves making the final design, refining and evaluating it. Finally, the project is presented in a final presentation and the design process is described in this report.

Figure 6. *Smart shirt project approach*



2.2. Methods

DESIGN METHODS

Throughout the project design methods were used to define the context, generate ideas and conceptualise them. The Delft Design Guide by Van Boeijen et al. (2020) was the source for most applied design methods and approaches.

EXPERT INTERVIEWS

Interviews with experts from Basalt, University of Leiden, Delft University of Technology, and other relevant parties offered valuable insights. These discussions primarily provided information about the previous smart shirt project and the rehabilitation sector, contributing to a detailed and accurate understanding of the context and potential opportunities.

PROTOTYPING METHODS

Several prototyping methods and approaches learned throughout the master's course Advanced Embodiment Design were applied. In the first phase rapid parallel prototyping was used to generate ideas and concepts. Iterative prototyping was applied to come to a working final prototype.

TESTING METHODS

Requirement-based testing ensured that each prototype met all technical and user criteria established during the development phase. In the final stages, a performance test was done to assess the movement visualisation. User tests were conducted to assess the prototype's usability and comfort. Moreover, the experts from the expert interviews were contacted to provide feedback as well.

Figure 7. *Prototyping in Applied Labs*

Figure 8. *User evaluation test*

Phase A

Discover

Phase A dives into the theory behind smart shirts. It gives an overview of literature study into smart textiles, rehabilitation sector, and IMU-based motion capture. Furthermore, the insights of interviews with rehabilitation doctors and physiotherapists are discussed. As well as an overview of the current smart shirt of Alamel and a benchmark of other prominent and interesting smart garments is discussed. The most important findings that need to be tackled in this project are highlighted.

This phase entails the following chapters:

Figure 9. *Physical therapy exercise at home*

3. Literature research

The discover phase started with literature research on the rehabilitation sector to understand the contextual background. It then explored smart textiles, examining their potential benefits and challenges. Lastly, there was looked into how IMU-based motion capture works and visualisation techniques.

3.1. Rehabilitation

Rehabilitation is conventionally seen as a disability-specific service needed by only few of the population. However, according to the World Health Organisation (2020) one in three currently could benefit from rehabilitation practises. Due to population growth and an ageing population an increase of 63 % from 1990 to 2019 is seen in cases in need of rehabilitation (see Figure 10). Furthermore, the corresponding years lived with the disability has risen with 79,4 %.

Figure 11 depicts the most prevalent conditions categories that would benefit from rehabilitation. In the age group from 15 to 64 years musculoskelatal disorder accounts for more than two thirds of the conditions.

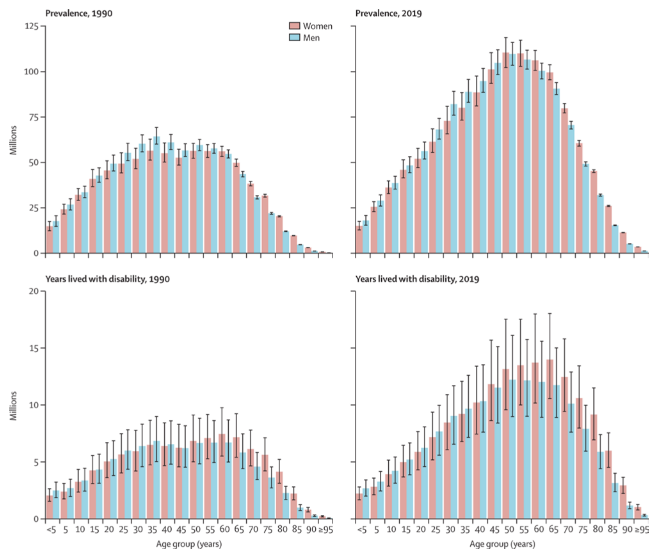


Figure 10. *Global number of prevalent cases with conditions that would benefit from rehabilitation and the corresponding years of life lived with disability by age and sex with 95% uncertainty intervals, 1990 and 2019 (Cieza & Alarcos, 2020)*

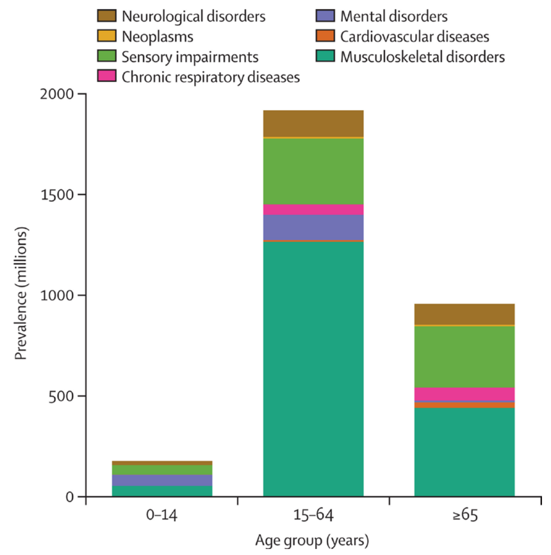


Figure 11. *Disease categories of prevalent conditions that would benefit from rehabilitation globally, by three age groups, 2019 (Cieza & Alarcos, 2020)*

Rehabilitation involves various interventions aimed at restoring mobility, strength, balance, coordination, and independence, while also managing pain and preventing complications. The goal is to improve quality of life and enable participation in personal, social, and work activities again. A significant part of rehabilitation is physical therapy, with 90% of therapy typically occurring at home (Arntz et al., 2023).

Home-based rehabilitation
As rehabilitation shifts to home-based programs to reduce costs and improve continuity of care, new challenges arise (Arntz et al., 2023). While home-based rehab offers flexibility, its success depends on patient adherence. However, up to 50% of patients fail to follow their exercise plans (Argent et al., 2018b; Jack et al., 2010), leading to reduced effectiveness, limited recovery, and increased re-injury risk.

Adherence is influenced by factors like self-efficacy, time constraints, pain, and social support, with self-efficacy being the strongest predictor (Wingood et al., 2024). Yet, it remains under-addressed in current practices.

Physical therapists address low adherence with simplified exercises and communication, but these methods often lack strategies that target self-efficacy and long-term engagement. To improve adherence, therapists should use real-time coaching, goal setting, self-monitoring, and patient education (Wingood et al., 2024). However, barriers like lack of knowledge and tools must be overcome for effective implementation.

Smart rehabilitation
The rise of data-driven and digital tools is transforming healthcare, and also rehabilitation. Wearable technology, including smartwatches and sports trackers, along with decision support systems, telemedicine, and "smart clinics", is improving care quality, reducing costs, and empowering patients and healthcare professionals (Nascimento et al., 2023; Chu et al., 2022).

Wearable devices are particularly useful for self-directed, rehabilitation at home. They are portable, cost-effective, and offer real-time monitoring, making them ideal for tracking body kinematics and assisting with posture and motion correction (Toh et al., 2023; Horak et al., 2014). IMUs have great potential for monitoring, self-assessment, real-time feedback, classifying home exercises for real-time coaching (Giggins et al., 2014) and promoting physical activity (Argent et al., 2018b). Recent studies show that even a single IMU can classify rehabilitation exercises and optimise rehabilitation strategies (Bavan et al., 2019).

Conclusion
As rehabilitation takes place mostly at home, adhering to physical therapy is a challenge, often due to low self-efficacy. A smart shirt offers great potential as a solution. It enables self-directed rehabilitation, providing real-time feedback and motion tracking to assist with exercises. Portable and user-friendly, the IMU-based smart shirt could allow patients to manage their rehabilitation at home while offering valuable insights for specialists. This technology could significantly improve patient engagement and long-term recovery outcomes.

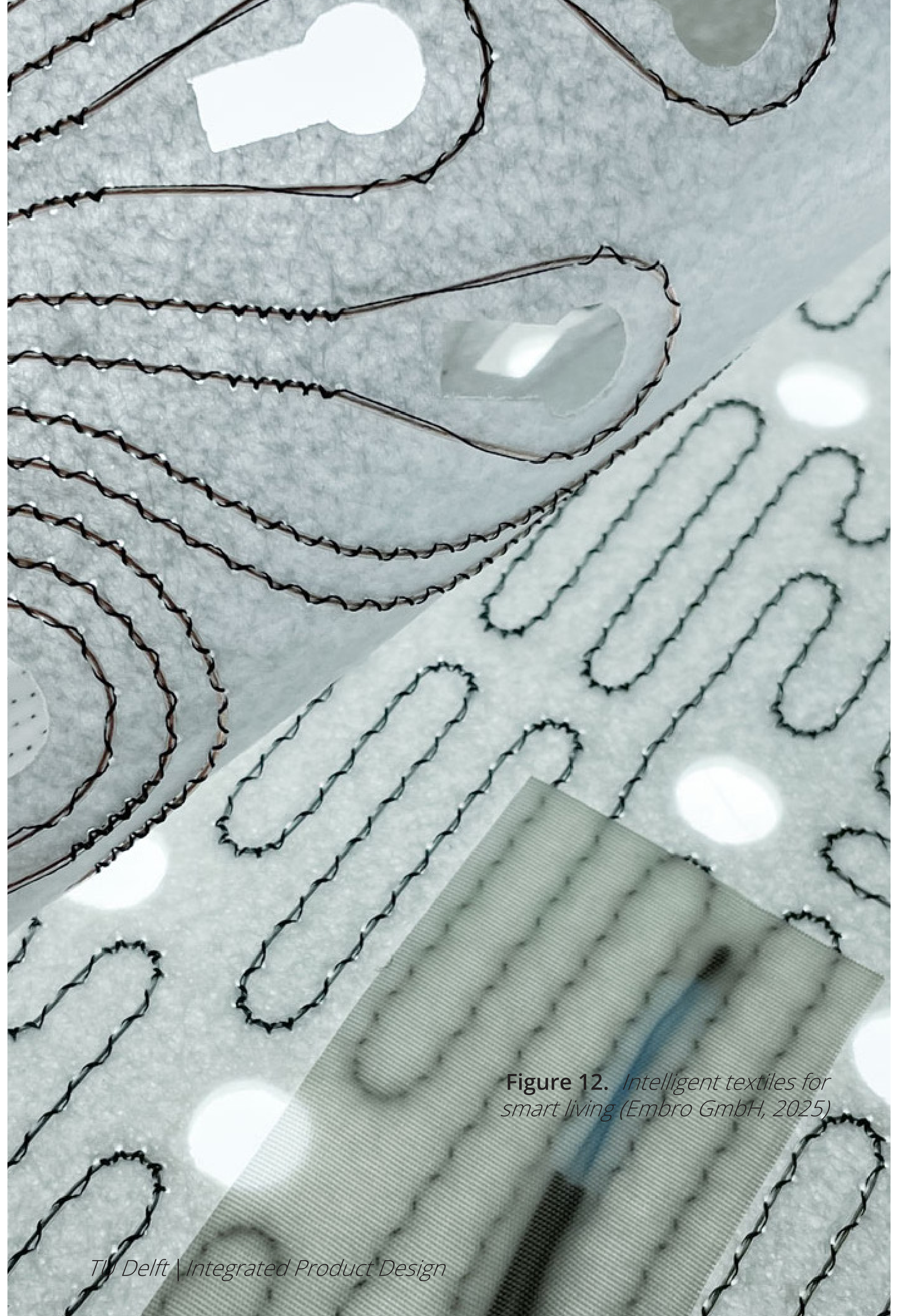


Figure 12. *Intelligent textiles for smart living (Embro GmbH, 2025)*

3.2. Smart textiles

The smart textile industry represents a rapidly growing intersection of fashion and electronics, expected to increase from USD 6.1billion valued in 2024 to 24.2 billion by the year 2031 (ReAnIn, 2025). With advancements in materials science and electronic integration, textiles have evolved beyond their traditional roles of protection, comfort and expression to become dynamic, interactive systems capable of sensing, responding, and even communicating. This transformation has opened up exciting possibilities across various sectors, including healthcare, sports, defence, and consumer wearables (Takebira et al., 2024).

Benefits & Opportunities
The increase in research popularity in the smart textile sector is due to the many benefits of combining electronics and textiles. This combination creates new opportunities, including:

NEW FUNCTIONS
Combining the possibilities of electronics with the possibilities of textiles opens a new world of functions not yet discovered.

MULTIFUNCTIONALITY
Smart textiles are capable of combining several features into a single garment. New combinations of characteristics and functionalities of typically fabrics and electronics can be made within one product.

SEAMLESS INTEGRATION
Advances in electronics miniaturisation and flexible materials enable the seamless incorporation of sensors, batteries, and circuits into textiles without compromising comfort. For example, conductive yarns and stretchable materials ensure functionality while maintaining the natural feel of fabric. (Mushi, Bigambo, & Mondal, 2024)

ECONOMIC POTENTIAL
The smart textile industry is a growing market with substantial economic promise. Increasing demand across sectors drives investment and innovation. Smart textiles contribute to creating new jobs in research, design, and manufacturing. (ReAnIn, 2025)

Barriers
The smart textile sector faces several key challenges that must be addressed to have lasting impact. This section highlights issues relevant to smart shirt design.

WASHABILITY
Unlike conventional textiles, smart textiles must protect embedded electronics during washing, as water and detergents can damage electronic circuits and connections, creating challenges for usability and long-term durability (Takebira et al., 2024; Mushi, Bigambo, & Mondal, 2024).

Smart textiles often use conductive yarns, which are vulnerable to mechanical wear from water, detergents, and heat, degrading their conductivity and structural integrity over time (SmartX Innovation Hub, 2024). However, new, more durable yarns are being rapidly developed, suggesting this issue may soon be resolved (Saty et al., 2024).

In addition, temperature limits for washing are strict. High heat can damage electronic components and adhesives. Many smart textiles require hand washing, reducing consumer convenience, and uncertainty remains about how many wash cycles these products can withstand before failing (SmartX Innovation Hub, 2024). The lack of standardised protocols for testing washability further complicates durability assessment, leaving consumers unsure about product longevity (Mushi, Bigambo, & Mondal, 2024).

SUSTAINABILITY
The integration of electronics into textiles raises sustainability challenges, adding to the already high environmental impact of the textile and electronics industries (Mushi, Bigambo, & Mondal, 2024). Smart textiles increase resource consumption, waste generation, and complicate waste management.

Smart textiles require rare earth metals and minerals, leading to habitat destruction, water pollution, and resource depletion. Textile production also consumes large amounts of water and energy, further increasing their environmental footprint. Additionally, non-biodegradable fibres, electronic waste, and pollutants from coatings and nanoparticles contribute to environmental harm.

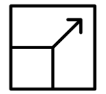
Waste management is particularly difficult. Reuse is limited because broken electronics render garments unusable, even if the fabric remains intact. Repairs are often impossible due to permanent connections between electronics and textiles. Recycling is also challenging, as embedded electronics interfere with textile recycling, and separating components for e-waste recycling requires much time.

VULNERABILITY

The physical demands placed on smart textiles present significant vulnerabilities, particularly related to the movement and stretching of the garment . These challenges can compromise the durability and functionality of the integrated electronic components and conductive yarns, ultimately limiting the product's lifespan and reliability. (SmartX Innovation Hub, 2024)

The natural movements of the wearer cause the fabric of the smart shirt to stretch, compress, and shift. This strain affects both the conductive yarns and the electronic circuits embedded within the textile. The following vulnerabilities are particularly critical: Repeated stretching and mechanical stress can degrade the conductivity and structural integrity of conductive yarns, leading to performance failures over time. The transition between soft textiles and hard electronic components are highly susceptible to breakage. Stress at these transition points often results in damage to the electronics, making the product non-functional (Alamel et al., 2024).

A single point of failure, such as a broken conductive yarn or damaged circuit, can make the entire smart shirt unusable. This lack of repairability exacerbates the product's vulnerability and contributes to its environmental impact through premature disposal.



SCALING UP

Another critical barrier to the widespread adoption of smart textiles lies in the challenge of scaling up from research prototypes to market-ready products. There is a significant gap between innovative smart textile research projects and the commercial viability of these technologies due to upscaling difficulties (SmartX Innovation Hub, 2024).

Smart textile designs often require techniques that differ significantly from conventional manufacturing methods used in the textile industry. This either requires changes to established production lines or forces changes in the product design to adapt to conventional techniques, both leading to resistance and slowing down the scale-up process and increasing costs drastically. The high cost of adopting new technologies and production methods often makes scaling up of smart textiles difficult to justify economically.

Conclusion

The viability of the smart shirt is supported by the rapidly growing smart textiles industry. A key opportunity lies in the seamless integration of electronics into textiles, which will be central to the design to create a comfortable shirt. Addressing the vulnerability of smart textiles, particularly the mechanical stress on conductive threads and transition points between soft fabrics and hard electronics, is crucial. These areas are prone to breakage, so solutions to enhance durability will be prioritised.

While washability, sustainability, and scalability are important, they will not be the primary focus for this initial prototype. However, the design will try not to limit the potential for these features to be implemented in future prototypes.

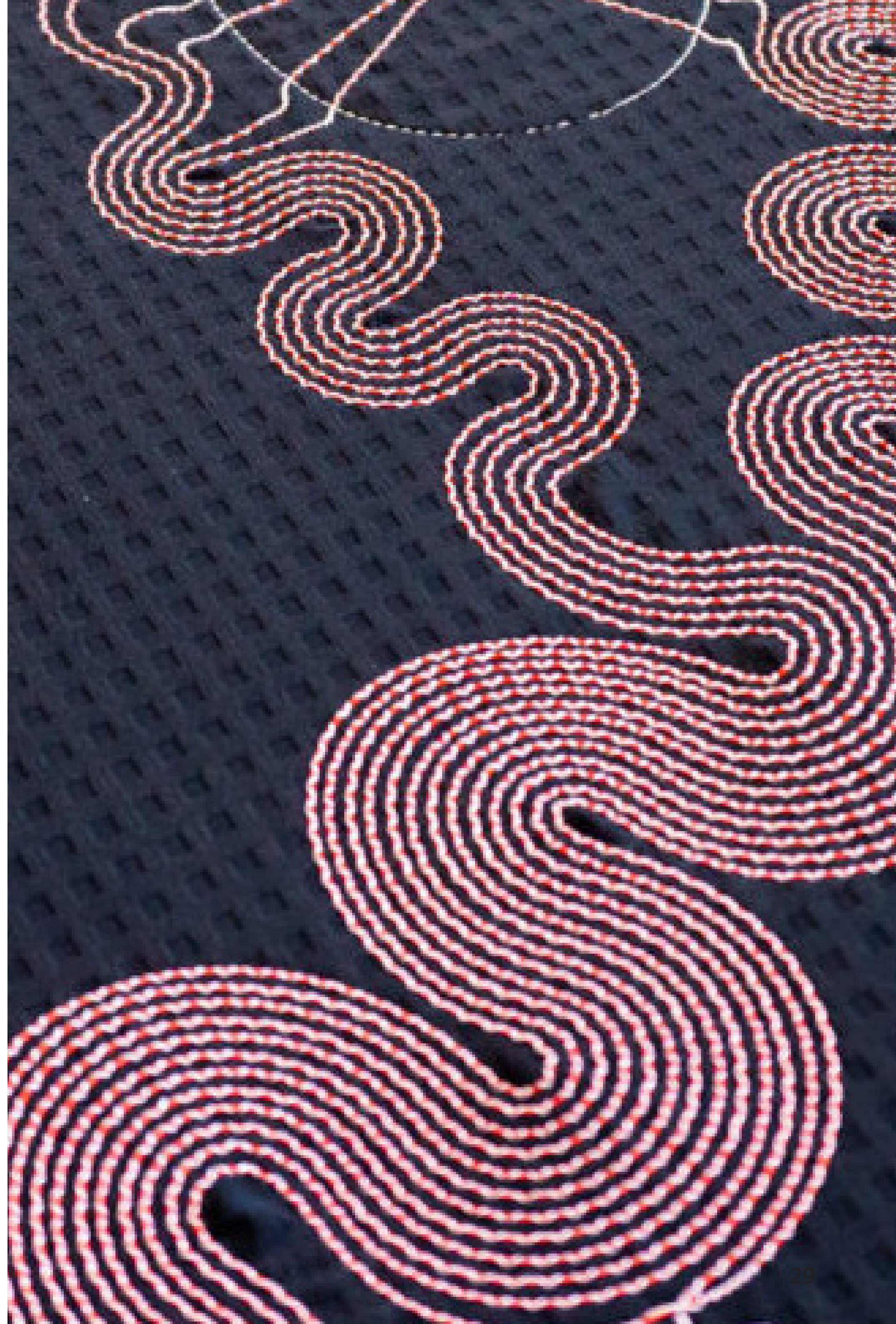


Figure 13. *E-textiles for body monitoring (Embro GmbH, 2025)*

Figure 14. *Dance movement captured (Photographic, n.d.)*

3.3. IMU-based motion capture

Motion capture records human movement for detailed analysis, widely used in healthcare, sports, gaming, and biomechanics. Various methods have their strengths and limitations. Optical systems use cameras and markers for high accuracy but need controlled environments. Depth cameras offer markerless tracking, suitable for casual settings. Stretch sensors embedded in garments track movement naturally and comfortably. A common approach uses wearable sensors like IMUs, which are portable, affordable, and effective in everyday environments (Stucovitz et al., 2018). IMUs, which include accelerometers, gyroscopes, magnetometers, and signal chips, are popular due to their low cost, flexibility, and comfort.

The use of IMU-based motion capture systems in rehabilitation has grown significantly. Accelerometers and IMUs are even the most frequently used sensors for motion capture in rehabilitation (Wang et al., 2017). A review by Gu et al. (2023) of 65 studies (2013-2022) found that most focused on rehabilitation assessment (82%), with fewer studies on training (12%) and both (6%). Stroke patients were the most studied group, with general rehabilitation, especially gait analysis, also widely researched. Gait analysis typically involved two IMUs to measure lower limb spatio-temporal parameters.

Key challenges include limited battery life and sensor drift, which impact training applications and upper limb studies. Future developments should focus on creating a highly integrated, multi-modal system with sensor fusion to improve wearability, functionality, and overall user experience (Gu et al., 2023).

IMU placement
Proper placement of IMUs is essential for accurately capturing upper body movements. Favata et al. (2024) reviewed where IMUs are placed on the upper body within research for movement capture in clinical applications. Figure 15 depicts the IMU placement used by the reviewed articles. IMUs are typically positioned on the following key anatomical (Acans et al., 2021):

Torso. Placing an IMU on the upper back or chest captures trunk movements and serves as a stable reference point.

Upper Arm. Attaching sensors to the lateral side of the upper arm ensures precise tracking of shoulder and upper arm dynamics.

Under Arm or Wrist. Mounting sensors on the lower arm near the elbow or on the back of the wrist monitors lower arm and wrist movements, as well as orientation.

Movement of IMUs independent of the overall body motion can compromise system accuracy. Common causes include soft tissue motion, muscle contraction, or shifting of the IMUs within the garment. To mitigate these issues, sensors should be placed on bony areas and integrated securely into the garment, ensuring a snug and stable fit. (Acans et al., 2021).

Figure 15. *Infographic of sensor placement (Favata et al., 2024)*

Calibration
Calibration is essential to ensure accurate and reliable data from IMUs by correcting for biases and misalignment. This process involves aligning the sensors to a known reference position to standardise their orientation and establish a baseline for motion tracking. One common approach in MoCap systems is pose calibration, where the user stands in a predefined posture that serves as a reference for all subsequent movements. (Morton et al., 2013)

While any pose can be used for pose calibration, common poses include the zombie pose, the soldier pose/N-pose, and the most widely used T-pose (see Figure 16) (Schepers et al., 2018, Morton et al., 2013). Pose calibration has disadvantages, including systematic errors if the user fails to execute or hold the pose correctly. These issues can affect calibration accuracy and, in turn, motion capture.

Other calibration methods include assumed alignment, where the IMU's axes are manually aligned with the segment axes; model-based, which estimates body segment anatomical axes using either a kinematic model or a statistical model of the joint; and augmented data methods, which use information from another source, such as optical motion capture, to determine the relationship between the IMU's frame and the body segment frame (Favata et al., 2024).

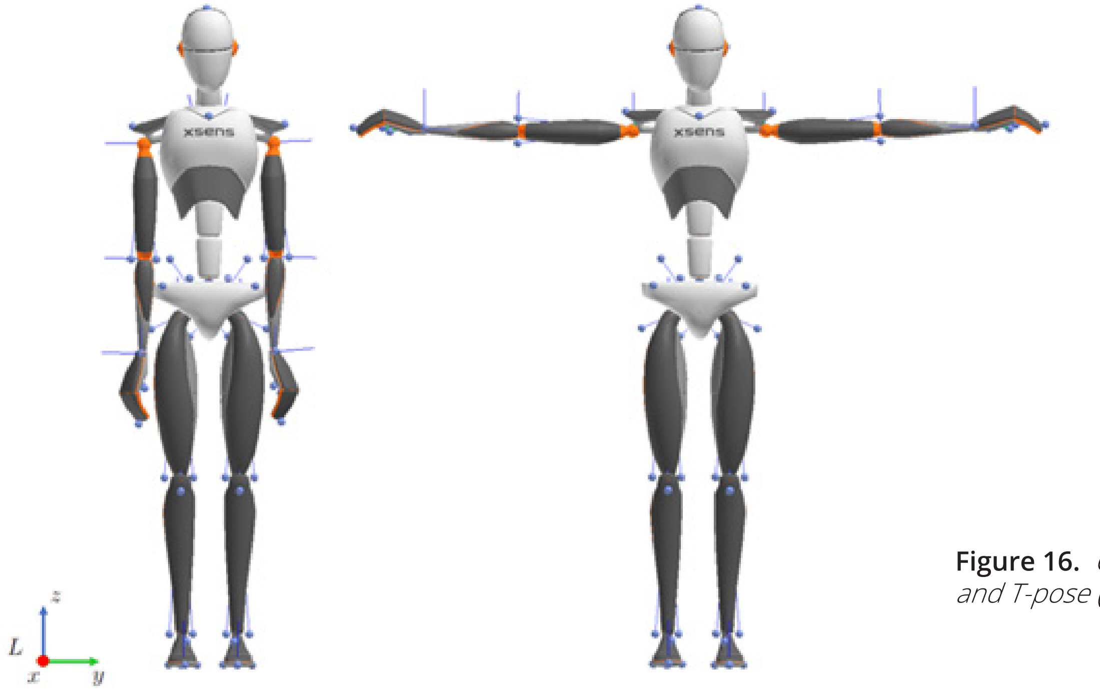


Figure 16. *Calibration poses: N-pose and T-pose (Schepers et al., 2018)*

Visualisation
Visualising motion from IMU data involves converting raw sensor outputs into body movement representations. The first step is aligning the data with a human body model, mapping it to joint angles or positions. Visualisation can be done by programming your own tool (Xsens, 2025; Zhang, 2017) or using tools like OpenSense and Blender.

OPENSENSE
OpenSense, part of the OpenSim framework, is a tool designed for analysing motion data from wearable sensors, like IMUs. It allows users to map IMU data onto a biomechanical model for visualisation and analysis of movement. OpenSense is especially valuable in clinical and research settings, used to assess movement patterns, study joint dynamics, and evaluate muscle behaviour (Borno et al., 2022). A key advantage of OpenSense is its user-friendly environment, which allows users to start with simple animations and gradually implement more advanced features

BLENDER
Multiple research projects and prototypes use blender as the tool to visualise motion capture (Nkeeline, 2020; Alvaroferran, 2016; Raghavendra et al., 2017; Checkered Bug, 2020). Blender is an open-source 3D software widely used in the film and game industry. In motion capture, it is a flexible tool for animating and visualizing movements from IMU data. With Python, Blender can import, manipulate, and render motion data to create accurate visual representations. One of Blender's strengths is its ability to produce highly customizable visualizations for aesthetics. However, it doesn't include human body characteristics by default, requiring manual adjustments for body sizing.

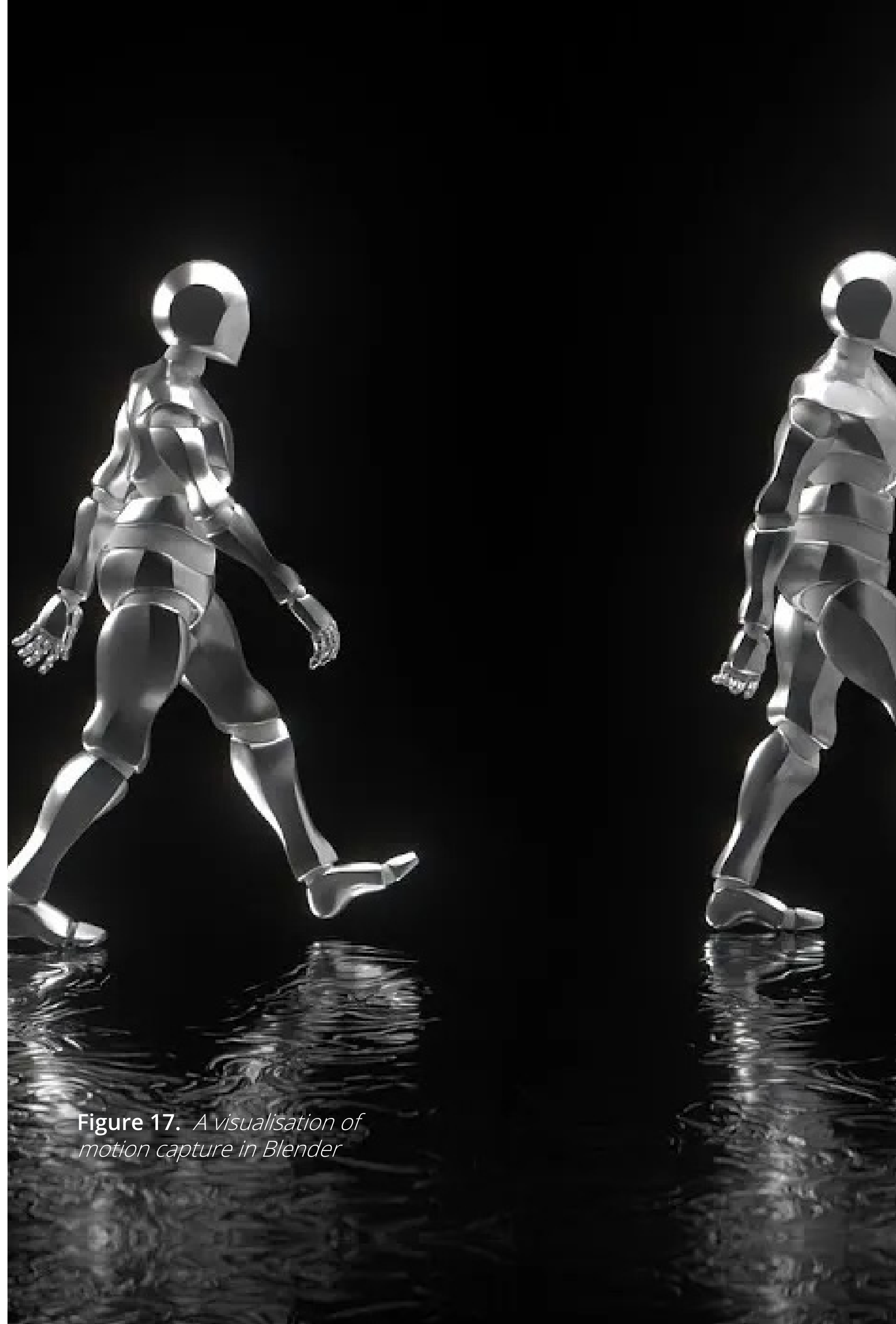


Figure 17. *A visualisation of motion capture in Blender*

Key Takeaways

Rehabilitation sector

- Two-thirds of people require rehabilitation, with 90% of this happening at home, yet 50% fail to adhere to their physical therapy plans.
- A key issue is often a lack of self-efficacy, which affects patient engagement and adherence.
- Rehabilitation specialists need more knowledge and tools to implement real-time coaching, goal setting, self-monitoring, and patient education effectively.
- A motion capture smart shirt could be particularly valuable as it is self-directed, home-based, portable, and assists with posture and motion correction, offering a practical solution to support patients' rehabilitation at home.

Smart textiles

- Smart textiles allow the integration of multiple functions and the seamless embedding of electronics into fabrics.
- Common barriers in smart textile development include washability, scalability, sustainability, and vulnerability. These challenges are also relevant to the smart shirt design.

IMU-based motion capture

- IMUs are popular for motion capture due to their low cost, flexibility, and comfort.
- Future developments should focus on creating a highly integrated, multi-modal system with sensor fusion to improve wearability, functionality, and the overall user experience.
- The placement of IMUs is crucial for accurate motion capture. Each essential part of the upper body needs an IMU to capture the rotational data.
- IMUs must be placed tightly on the skin, preferably on bony areas where muscle contraction will not affect the readings.
- IMU calibration is necessary to adjust for the starting position, which can vary for each person. The easiest approach is position-based calibration.
- Visualisation can be achieved either by programming custom tools or by using existing visualisation programs.
- OpenSense is a medical visualisation tool, while Blender is focused on animation but can also be applied in the smart shirt design for visualising motion.

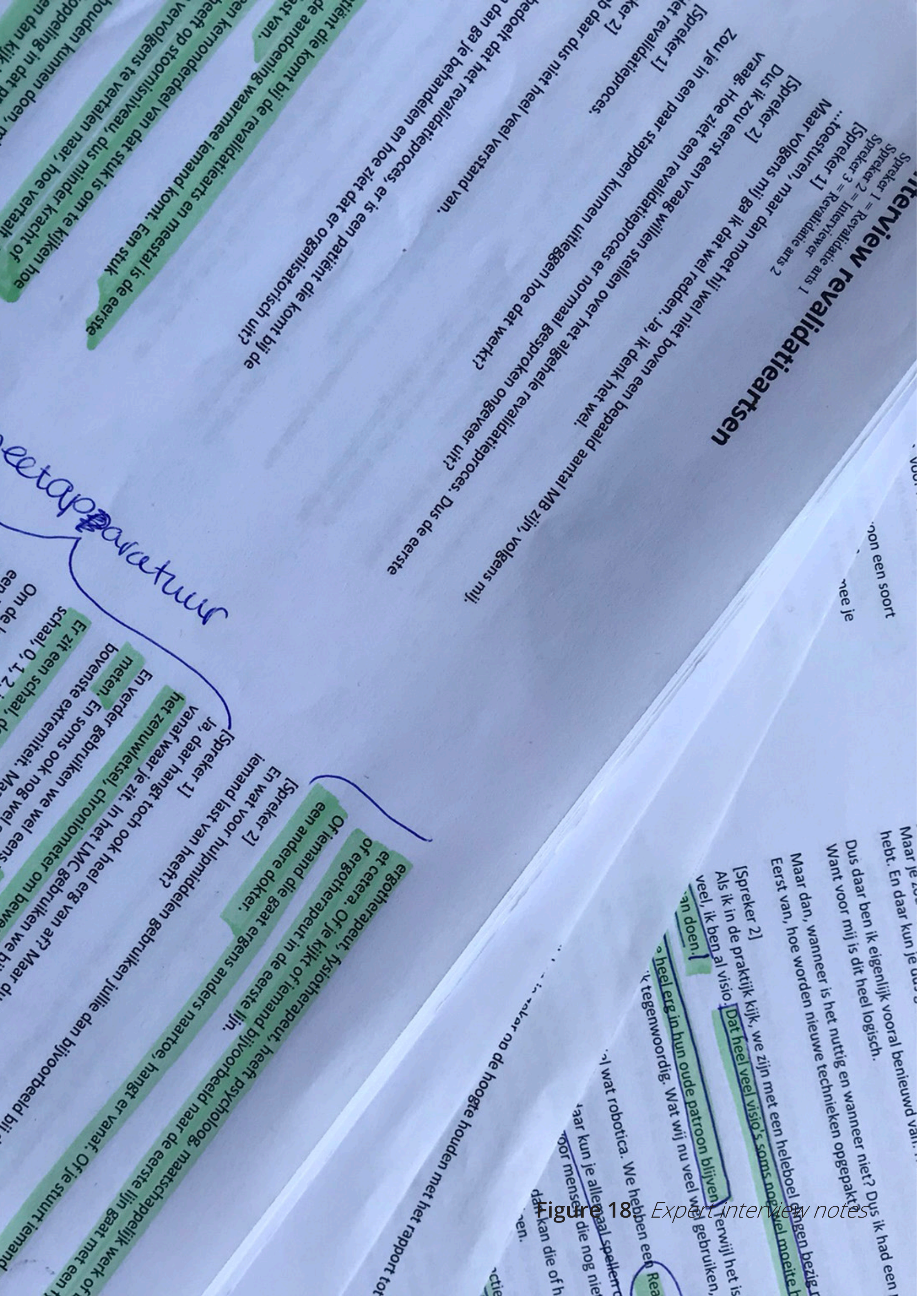


Figure 18. *Expert interview notes*

4. Additional research

This chapter presents additional research done to better understand the rehabilitation sector, including expert interviews. It also reviews existing motion capture smart shirts, including the Alamel et al. (2024) prototype, and benchmarks other IMU-based smart wear.

4.1. Expert insights in rehabilitation

To gain a detailed understanding of the rehabilitation sector, two expert interviews were conducted with the University of Leiden and Basalt rehabilitation centre. The goal was to explore the rehabilitation process, identify where a smart shirt can add value, and define its requirements for both specialists and patients. Figure 19 shows the research questions used.

Methodology
The first interview was with P.M. Dekker and J.H. de Groot, rehabilitation doctors at LUMC, and the second with a rehabilitation physiotherapist of Basalt, and B. Janse, a rehabilitation physiotherapist and innovation manager at Basalt rehabilitation centre Den Haag.

The semi-structured interviews, guided by the questions in Appendix B, focused on different aspects: the first addressed the rehabilitation process (RQ1) and challenges the shirt could address (RQ2), while the second focused on the possibilities and requirements of a smart shirt (RQ2 and RQ3). Insights from both interviews were used to answer all research questions.

The first interview was conducted online, and the second at Basalt in The Hague. Both were approximately 30 minutes long. The first interview included a visual of Alamel et al.'s concept, and the second included a demo of the initial blender visualization setup (see Visualization of Motion Capture). All interviews were conducted in Dutch, recorded with informed consent.

Analysis
The insights from both interviews were combined, as they covered similar topics. They were analysed by identifying key quotes and organizing them into themes (see Appendix D) (Method from the Delft Design Guide (2021)). Within these themes, insights emerged as statements. The original Dutch quotes were translated into English for this report.

Results
The results are separated in five themes: steps in the rehabilitation process, technology within rehabilitation, patients characteristics, smart shirt applications and smart shirt requirements. Here the statements per theme are shown accompanied with the associated quotes.

RQ1.	What does the rehabilitation process look like?
RQ2.	How could a smart shirt contribute to the rehabilitation process?
RQ3.	What are the requirements for a smart shirt from the perspective of a rehabilitation doctor, physiotherapist, and patient?

Figure 19. *The research questions for expert interviews*

Steps in the rehabilitation process
The rehabilitation process begins with an intake and diagnosis phase where medical history and physical examinations are crucial. Special attention is given to assessing disorders at muscle, movement, and function levels.
"*The first intake is somewhat dependent on the condition someone comes with. A piece of anamnesis, so what is someone suffering from a piece of physical examination*" - doctor 1
"*A core component is to see how complaints at the disorder level, such as reduced strength, translate into problems in daily life*." – Doctor 1

The rehabilitation process differs greatly per patient, dependant on their diagnosis.
"Very broad, different" - doctor 1

After the initial assessment, a treatment plan is developed, often in a multidisciplinary setting. Depending on the severity and nature of the complaints, the patient might be referred to primary care or treated within the rehabilitation centre itself.
"*The initial treatment plan and the next steps for a patient often involve either self-treatment with a team of professionals such as an occupational therapist, physiotherapist, psychologist, social worker, or movement pedagogue, or they may proceed with first-line physiotherapy or occupational therapy. In some cases, patients are referred to other specialists, such as a different doctor or clinic, depending on their needs*."- Doctor 1

The physiotherapy process includes scheduled meet ups and prescribed exercises to be performed at home.
"*Actually, your rehabilitation mostly takes place at home*." - Physiotherapist 1

Technology within rehabilitation
Many of the evaluations, done by physiotherapists and rehabilitation doctors are based on visual observation and clinical experience, because it is fast, easy and can cover multiple aspects at once.
"I can observe everything fairly well with the naked eye."
– Physiotherapist 1
"*We try to measure many things by feel, but for more extensive research, we use EMG and cameras*." – Rehabilitation doctor 2

Tools are used to make measurements objective and to track progress. There is a need for a more reliable method to document patient progress, which not only incorporates test scores but also visual data of poses and movements.
"If you're unsure whether he has made progress or not, or whether he didn't do it last week, then there is simply more objective progress." - Physiotherapist 2
"*Filming is now used to document progress/current situation*." - Physiotherapist 1

Physiotherapists are generally open to new technologies, but many still prefer sticking to traditional methods.
"Many physiotherapists still struggle to do something new because they stay in their old patterns." – Physiotherapist 2

New technology tends to be accepted more quickly when it provides clear value, is easy to use, doesn't cause discomfort to patients and decreases the overall workload.
"*We really look at what value it has and how easy it is to use. [..] it should not hinder the patient"* – physiotherapist 1
"We really can't take on more. It needs to either replace something or be something the patient can do on their own." – Physiotherapist 2

Patients characteristics
Patient that could benefit from the shirt are patients with neurological and orthopaedic disorders and patients with compensatory movements. For patients with neurological disorders, such as stroke, the smart shirt can provide valuable insights into movement patterns, particularly for those with spasms or hypertonia in the arm.
"Patients with a stroke often have problems with strength or spasms in the arm." – Physiotherapist 2

Most patients are highly motivated to get well, especially if they understand the goal and reason behind the treatment.*"People who are very aware of what has happened, what they were able to do before, and who have a clear goal , they want to return to work and are highly motivated , that's not the problem*." - Physiotherapist 2, "*Chronically ill people are not always highly motivated, or individuals who, due to their injury, lack insight into their condition."* - Physiotherapist 1

Smart shirt applications
The smart shirt could be used for therapeutic or diagnostic purposes.

THERAPEUTIC APPLICATIONS
The smart shirt can monitor compensatory behaviour by detecting asymmetric movements, which is crucial for patients with acquired brain injury, other motor impairments, or due to pain. *"Compensatory movements, such as trunk rotation or lifting an elbow, are currently not well measurable."* - Physiotherapist 2, "*In ABI patients, you often see them compensate by using different muscles. It would be interesting to visualize that."* – Physiotherapist 2

For orthopaedic patients, the shirt can highlight how movement restrictions due to joint issues impact functionality. *"In joint disorders, people can move less well due to pain or stiffness."* – Physiotherapist 2

The shirt can also provide feedback during exercises, using haptic or visual cues to help patients improve functional movements. "*Subtle feedback, like a green light or a slight vibration, can be very effective in correcting movement*." – Physiotherapist 1

The shirt can enhance motivation through gamification, especially for chronically ill patients who may struggle with motivation. "*Chronic patients aren't always motivated. A gaming element can really help*." - Physiotherapist 2, "*I think it would then be used more as a therapeutic tool, possibly in the form of a game. Something along those lines, rather than purely diagnostic."* - Physiotherapist 1

The shirt can support daily tasks by monitoring activities like cooking or folding laundry, while simultaneously integrating exercises. "*You can use it for a task like folding laundry and combine it with exercise*s."
- Physiotherapist 1

The visualisations could be used as a communication tool to explain exercise movements and reflect on patients performance. "*Visualization would be interesting for me as well. But more to be able to explain things to the patient. So, what you're saying, being able to present it in a way that surrounds the information, is definitely interesting."*- Physiotherapist 2

DIAGNOSTIC APPLICATIONS
The shirt could visualise the movements in one go, replacing the need of doing a lot of different tests.
"I think what would be really valuable is if you could visualise your movements, because we don't do that right now. There's almost no place where we look at how someone moves their arm because it's a lot of hassle. So, we rely on many clinical tests instead." - Doctor 2, "*And coincidentally, we are really looking for ways to capture those movements for the upper extremity*."- Doctor 1

The shirt can help document objective progress by measuring improvements in angles, speed, and symmetry of movements.
"*It could be useful to see objective progress, like how symmetrically someone moves*." - Physiotherapist 2
"It allows for a more objective assessment of the effects of interventions. Currently, measuring with a goniometer before the intervention, then afterward, is quite imprecise." - Doctor 1

Goniometers and other tools have limitations in precision and depend on the expertise of the physiotherapist.
"*We measure angles with a goniometer, but the question is whether this shirt could make it more useful*."
- Physiotherapist 1

The shirt could give insight into how people move at home.
"Curious about what people do at home and how they move at home."- Doctor 2
"*It provides a lot more data beforehand before someone comes in*." - 1
"You would then need to have some kind of logbook."- Physiotherapist 1

Requirements of the shirt
The shirt must be easy to put on, even for patients with limited mobility. "*It has to be easy to put on, especially for people who struggle with sequential tasks*." - 2, "*Most patients we see with arm/shoulder problems are affected on one side and almost all of them have a good arm. With one arm, you can still do quite a lot (such as putting on an elastic shirt)*." - doctor 2

The shirt needs to be comfortable, ensuring that it does not restrict movement. "*You want the sensors to be placed correctly without the shirt being too tight or sagging*." - 2
The shirt must be durable and easy to clean. "*You need to ensure that the hard parts don't break easily and that it's easy to wash*." - Physiotherapist 2

The precision of measurements is crucial, meaning that the placement of the sensors must be accurate with minimal margin for error. *"If you place the shirt just one centimetre lower, how error-prone is that?*" - Physiotherapist 1
The shirt should be suitable for an exercise session of 10 minutes within a rehabilitation meeting context. "*Our treatments usually last half an hour, including setup and charging, so it needs to be quick to set up and start. If it takes longer than 10 minutes, no one will use it*." - Physiotherapist 2, *"A battery lasting an hour would already be enough for an exercise session."*
- Physiotherapist 2

Calibration of the shirt must be done independently of standard poses. *"For accelerometry, you need a kind of standard pose to then calibrate all your sensors. What is horizontal, what is vertical, and so on. A T-pose is often used for this, but some patients can't do that. So, it should actually be independent. A selection menu wouldn't be specific enough*." - Doctor 2

Discussion

Throughout the interviews, there was a notable curiosity about the potential of the smart shirt, which underscores its appeal and relevance in the rehabilitation sector. Interestingly, while rehabilitation doctors were primarily focused on improving diagnosis methods and detailed numerical analysis and discussing various future scenarios, physiotherapists concentrated more on practical applications and the direct impact on patients.

RQ 1 What does the rehabilitation process look like?

The themes Steps in the rehabilitation process, Use of technology, and Patient characteristics gave insight in the rehabilitation process. There is a consensus among all experts that the rehabilitation process is highly personalised but typically involves phases of intake, diagnosis, and treatment planning. The frequency of visits to rehabilitation doctors varies depending on the patient's condition, whereas physiotherapy sessions are typically scheduled twice a week for about 30 minutes. In terms of tools, while rehabilitation doctors use a mix of equipment, physiotherapists predominantly rely on visual observation and occasionally use a goniometer. New technologies are embraced by physiotherapists when they clearly add value, are easy to use, do not discomfort patients, and help reduce their overall workload. A variety of diagnoses were mentioned, illustrating the diverse group of patients that could benefit from a smart shirt. Most patients are described as highly motivated, particularly when they understand the treatment rationale, though some patients with chronic conditions or lacking awareness of their diagnosis require more motivation to engage in therapy.

RQ 2 How could a smart shirt contribute to the rehabilitation process?

The interviews identified potential applications for the smart shirt, categorised into diagnostic and therapeutic uses. Rehabilitation doctors see potential in both applications, but physiotherapists prefer therapeutic applications, questioning the efficiency, reliability, and practicality of a diagnostic tool. Doctors highlighted the value of objective measurements, such as using the shirt for "a gait analysis for the upper body," and expressed significant interest in monitoring patient movements at home. In contrast, physiotherapists were sceptical about the utility of extensive data without contextual information, naming constraints in time and expertise for thorough data analysis.

The idea of a communication tool to explain treatments and progress resonated more with physiotherapists and was less emphasised by doctors.

All experts acknowledged the potential of integrating motivational tools into the smart shirt. Existing therapeutic devices like REAtouch and REAplan, which transform therapy into engaging activities at rehabilitation centres, demonstrate that gamification could significantly enhance patient engagement.

The concept of error-less learning received unanimous support from the experts. A smart shirt that provides real-time feedback could foster this approach by continually guiding patients toward correct movements, ensuring an effective balance of positive and negative feedback.

RQ 3 What are the requirements for a smart shirt from the perspective of a rehabilitation doctor, physiotherapist, and patient?

Rehabilitation doctors would like to have visualisations coupled with movement data. A specific warning was given that pose calibration, often used in motion capture devices, is not suitable, because patients have difficulty with standing in a particular pose. Physiotherapists emphasised requirements from a patient-centric perspective, highlighting the need for comfort, diverse sizing, ease of use for individuals with physical or cognitive limitations, durability, and robustness. The experts collectively stressed that if the smart shirt is to be used diagnostically, its precision and reliability must significantly surpass current tools and methods.

Conclusion

The rehabilitation experts see great potential in an IMU-based motion capture shirt. They highlighted a wide range of applications, both therapeutic and diagnostic. However, for this project, the focus on therapeutic tools combined with a visualisation system is more appropriate, as a diagnostic tool would need to surpass current tools and methods, which is beyond the scope of the first prototype.

Experts emphasised that the shirt should not only have a proper working motion capture system, but must also meet the needs of patients. It should fit perfectly into the rehabilitation process to ensure it is used. Given the diversity of patients in rehabilitation, the shirt must be flexible to accommodate varying needs.

Additionally, the design must be simple, taking into account that some patients may have cognitive impairments, and rehabilitation specialists do not have the time to learn a new tool.

The insights gathered from the interviews will guide the next steps, helping to map the rehabilitation context, scope the project, and define the requirements for the shirt.

Figure 20. *The final prototype of smart shirt of Alamel et all. (2024)*

4.2. Current IMU-based motion capture garments

This section reviews the current landscape of IMU-based motion capture smart garments, focusing on existing solutions on the market and in research. It starts with a summary of the Alamel project, followed by a review of other relevant projects in the field.

Smart shirt design of Alamel et al.
This project builds on the smart shirt concept developed by Alamel et al. (2024), which was designed for at-home physiotherapy. The purpose of the shirt is to monitor and capture the user's upper body movement and respiratory rhythm during exercise. Alamel et al.'s project focused on understanding the requirements of such a wearable, exploring these through small prototypes, and demonstrating the concept with a working prototype (see Figure 20). To understand its functioning, the challenges faced, and which elements can be improved, a detailed analysis was conducted. This involved reviewing the project report, examining available small prototypes, and conducting an interview with one of the designers (see Appendix C).

FEATURES OF THE CURRENT PRODUCT
The product is a stretchy shirt with a sporty look. The shirt is embedded with five IMUs, which are connected using embroidered conductive yarn to a multiplexer, an Arduino Nano, and a battery. The BNO055 and MPU9264 sensors capture rotational data of the user. An additional Python script reads the Arduino serial monitor and uses the data to create a visualisation with OpenSense software, using the IMU Inverse Kinematics function (see Figure 21 for the visualisation).

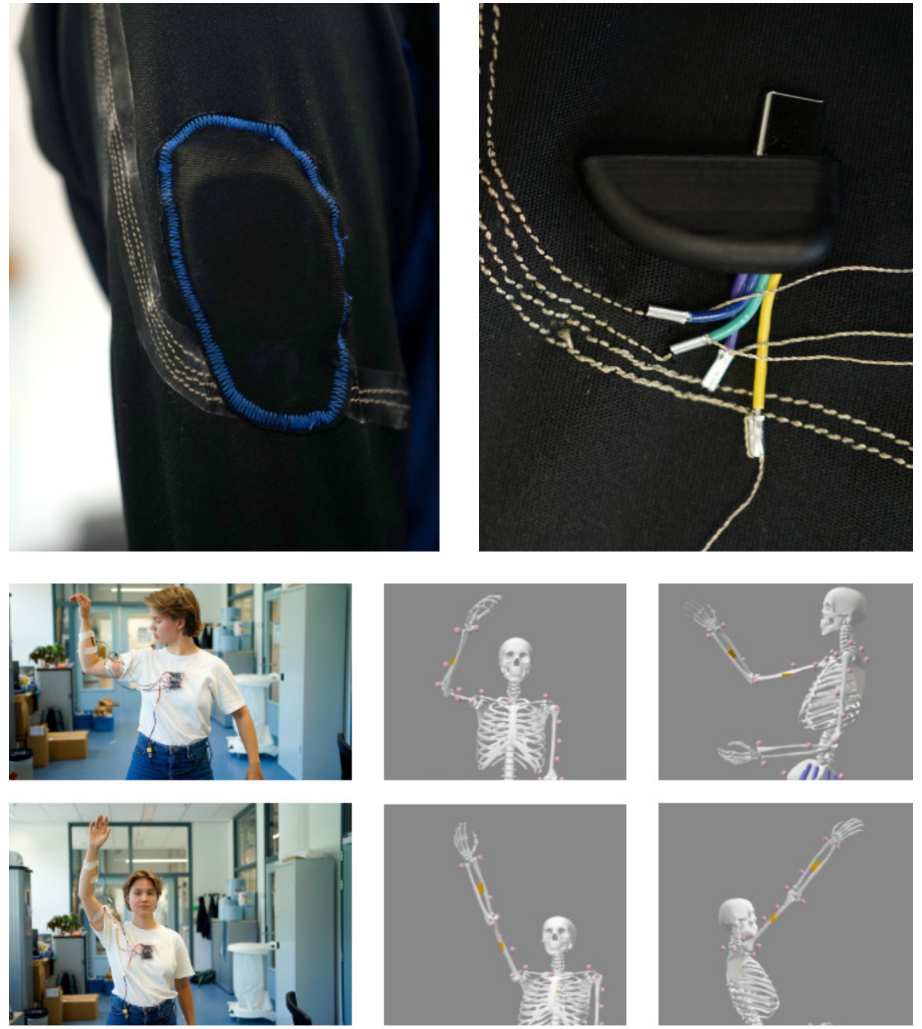


Figure 21. *Smart shirt prototype of Alamel et all. (2024): IMU integration, conductive wire connections and visualisation of motion capture*

INSIGHTS RESEARCHER
An interview was conducted with one of the designers of the smart shirt of Alamel et all. (2024) to get a deeper understanding of the made design choices, the design approach and faced obstacles. The information gathered form the interview was mostly an addition or an explanation to the report. Therefore, the interview results are taken together with the report analysis and incorporated in the main research findings and the painpoints. For a detailed overview of the interview results see Appendix C.

MAIN RESEARCH FINDINGS
The project explored various aspects, including aesthetics, physiotherapy applications, IMU sensors, electronics setup, and textile design. Key findings include:

- IMUs should be placed on bones to avoid muscle contraction affecting motion capture.
- While MPU9265 sensors are cheaper, they were less reliable, particularly for movements like pronation. BNO055 sensors were experienced as more reliable and still affordable.
- Physiotherapists recommend this design for long-term injury rehabilitation, as it may be too complex and expensive for short-term use.
- Users tend to move more carefully when wearing the shirt due to concerns about damaging the sensors.

PAIN POINTS
Based on the Alamel design, the following issues need further research or improvement:

IMU placement. The loose fit around the wrist causes the IMUs to misalign when the user moves, which affects motion capture accuracy.

No real-time coupling. The shirt does not use a real-time visualisation, which means that users cannot see immediate results.

USB-C connections. The tight USB-C connections make it difficult to remove sensors and risk breaking the conductive thread (see Figure 22).

Non-stretch conductive thread. The lack of stretch in the conductive thread can cause breakage when integrated with a stretchy fabric, leading possibly to loss of connection over time.

Lack of wireless connectivity. Without wireless capabilities, the shirt must use a wire or store data, which is impractical for physiotherapy exercises.

No motion capture. Despite being powered, the IMUs fail to capture movement data, suggesting a hardware or software issue.

Shirt overheating. The shirt tended to warm up during use, likely due to the high resistance of the conductive thread or plastic covers on the sensors.

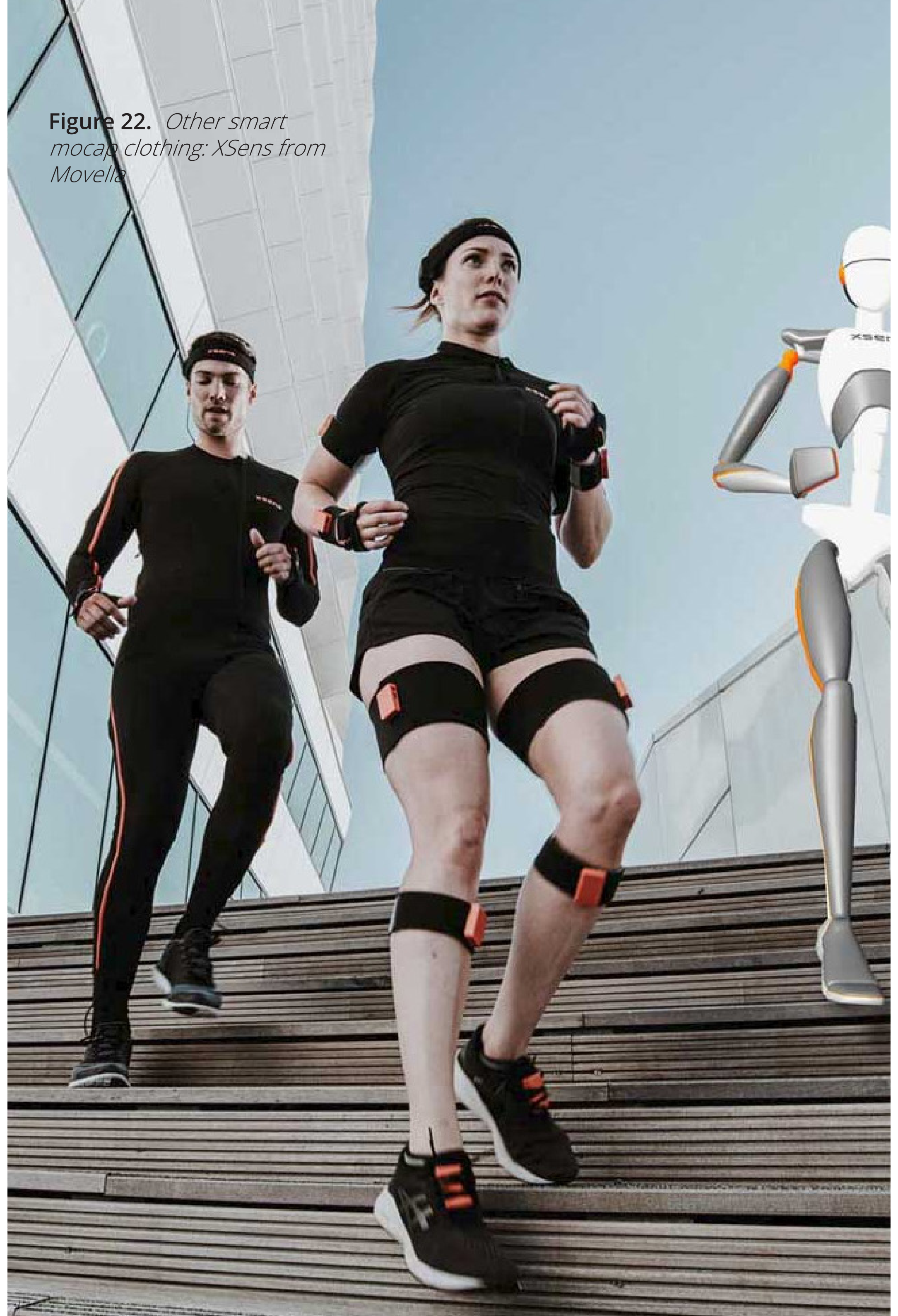


Figure 22. *Other smart mocap clothing: XSens from Movella*

Other motion capture clothing
In addition, other IMU-based motion capture garments were reviewed to understand their approach. A brief benchmark study was conducted to collect relevant information (see Appendix E). The three most notable projects are highlighted here (see Figure 22).

XSENS
Xsens is a leading company in the field of motion capture technology, renowned for its applications in the film industry, sports, and the medical sector. The system includes 17 IMUs attached to multiple individual straps, offering detailed and flexible tracking of the body. Its advanced technology has been extensively validated through numerous studies, underlining its functionality and reliability. Although well-known among rehabilitation doctors, the high cost, ranging from several thousand to tens of thousands dollars, along with the need for professional attendance, limits its widespread popularity in clinical settings. (Xsens Products | Movella.com, 2025)

SMART TIGHTS TU DELFT & KNVB
Developed by TU Delft and KNVB, these smart tights are engineered for high-performance sports. The design integrates five IMUs with conductive thread integrated in elastic band to collect detailed movement data, which support soccer players to improve their techniques and prevent injuries. A key aspect of the research was to validate the reliability of the motion capture technology, which involved comparative testing against traditional camera systems. In addition to technical efficacy, a significant focus was placed on the comfort of the tights, ensuring they are suitable for extended use during soccer activities.

SMART SUIT, ACANS ET ALL.
The Smart Suit is a research prototype by Acans and colleagues at the Institute of Electronics and Computer Science at the University of Latvia (2021). The garment is tailored for diverse applications across physiotherapy, rehabilitation, and sports settings. It incorporates 15 BNO055 IMUs, which are embedded into a tightly fitted whole body suit with elastic wired connections to maximize comfort and robustness. Priced at approximately €500, the Smart Suit excels in performance, offering superior characteristic parameters in comparison to other IMU-based systems available on the market. Notably, it maintains continuous data accuracy, showing no data loss even when benchmarked against the camera-based BTS SMART DX system.

Conclusion
The research of Alamel et al. on smart shirts for motion capture sets a solid foundation for future development. Their setup and insights highlight critical requirements and pain points, providing starting points for improvement. However, there should be taken a careful look at the motion capture system, especially when integrated in the shirt.
By examining other smart garments, possible solutions for the painpoints were found. Moreover, inspiration can be taken from these projects with the goal to leverage the best practices from the field of motion capture clothing.
Lastly, this benchmark will be used to compare the final result of this project to, to uncover the added value of the prototype.

Key Takeaways

Rehabilitation experts

- The rehabilitation process is highly personalised, with physiotherapists focusing on practical applications and rehabilitation doctors on diagnoses.

- A motion capture system with a visualisation focus can have multiple future applications in the rehabilitation sector. Rehabilitation doctors see potential in the smart shirt for both diagnostic and therapeutic uses, while physiotherapists value its therapeutic potential, but are concerned about the need for extensive data.

- The smart shirt needs to be comfortable, durable, and patient-centric, especially for those with physical or cognitive limitations, to make the product viable in the future.

- Most patients are not able to execute pose calibration, which limits common motion capture methods. The project has to find a way around this.

Current IMU-based motion capture garments

- The prototype by Alamel et al. has a solid integration setup, but the integration in the shirt can be improved, with a focus on making the shirt more functional and robust.

- BNO055 sensors are considered the most reliable, affordable, and compact, with built-in sensor fusion, making them suitable for use in a motion capture smart shirt.

- Most IMU-based research is highly technical, often overlooking integration methods and failing to focus on the user experience.

- Commercial smart wear performs well but is extremely expensive, limiting its accessibility.

Phase B

Define

The define phase aims to specify and narrow the design goal, target group and design solutions. This chapter will describe a created rehabilitation journey, the target group and structures the functions of the smart shirt. It concludes with a list of requirements with which the design later on can be evaluated.

This phase entails the following chapters:

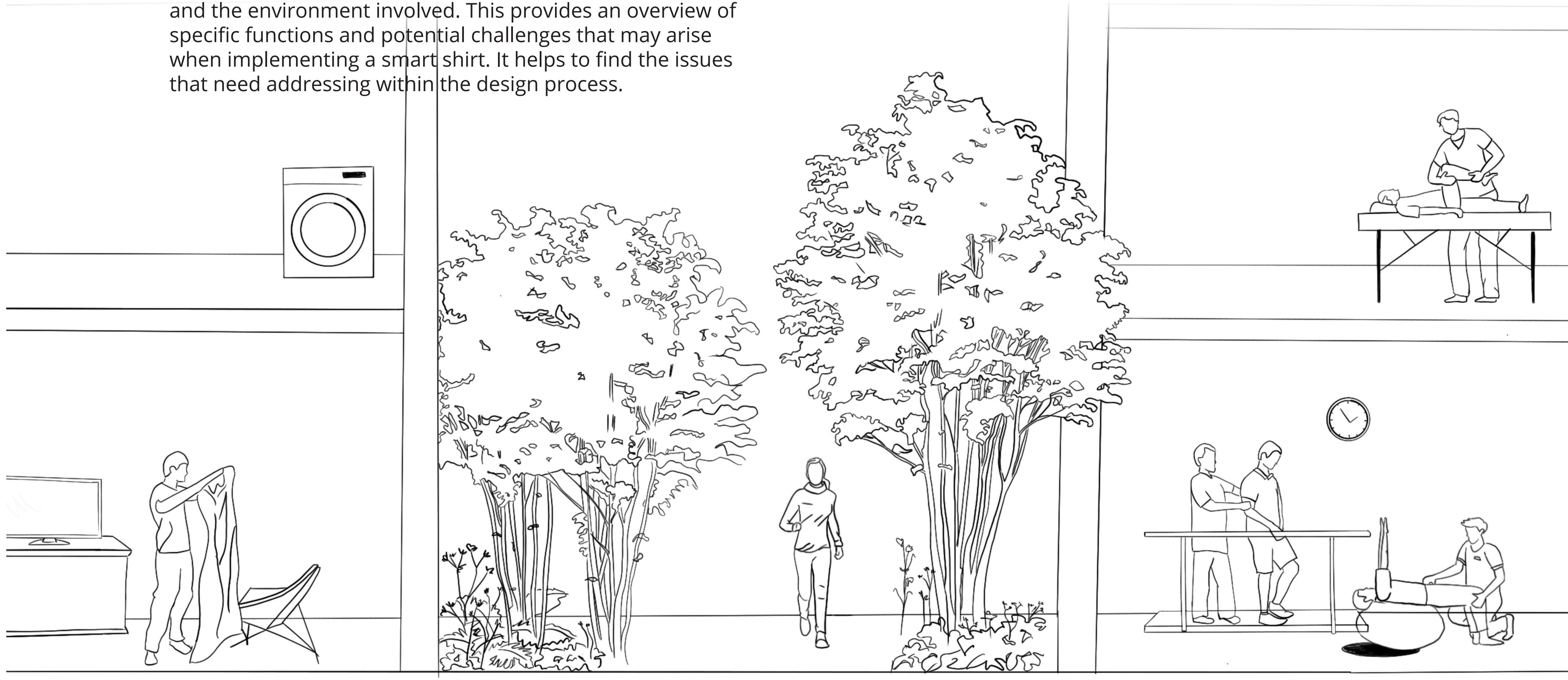
Figure 23: *Mapping the sewing pattern*

5. Mapping the rehabilitation context

This chapter brings the information from the literature research and the expert interviews together, by further defining the rehabilitation context were the smart shirt will be implemented. It starts with a sketch of the physical context, then a general rehabilitation journey and finally the current tools are discussed.

5.1. Physical context of the rehabilitation smart shirt

Rehabilitation happens in different physical contexts. It is mostly done at home but also outside or at the rehabilitation centre, three totally different contexts. These situations are illustrated in Figure 23, showing the activities, objects, and the environment involved. This provides an overview of specific functions and potential challenges that may arise when implementing a smart shirt. It helps to find the issues that need addressing within the design process.



Insights

Storage & durability. Users will maybe store the shirt with other sports attire in a bag, requiring it to be robust, foldable, and able to withstand transport without damaging the embedded technology.

Outdoor environments. Outdoor use introduces factors like rain, wind, and physical impacts, needing weather resistance, durability, and alternative visualisation methods.

Home use. Patients need an intuitive design with clear instructions to use the shirt effectively without expert supervision.

Maintenance. The shirt should be washable without damaging the embedded sensors, accommodating regular laundry cycles.

Technology compatibility. It should work with common devices and have a charging solution compatible with standard plugs. The shirt should be compatible with existing rehabilitation devices. I should also be possible to use it within group activities like walking classes.

Ownership & personalisation. Ownership impacts customisation, maintenance, and cost considerations, whether the shirt is personally owned or provided by the therapy centre.

5.2. Rehabilitation journey

Designing a smart shirt for rehabilitation requires understanding the full rehabilitation journey, including physical, emotional, and practical challenges. By addressing these aspects, the shirt can be tailored to meet key needs, adding value and ensuring a user-centred design that enhances the patient's experience.

Journey Mapping

The Journey Mapping method from the Delft Design Guide (2021) was used to outline the patient's rehabilitation time line, from injury to full recovery. The stages are mapped horizontally, with themes like rehabilitation phases, emotions, challenges, and potential smart shirt applications mapped vertically. Information was gathered from expert interviews, Alamel et al.'s report, and the rehabilitation literature.

Figure 24 shows the journey's four stages: injury, acute recovery, regular rehabilitation, and long-term maintenance. The journey varies for each patient, with some stages skipped or starting from the middle in case of re-injury. The first stage begins with an injury or condition worsening, followed by self-care and a diagnosis, leading to a treatment plan. The second stage involves acute recovery, including potential surgery, followed by physiotherapy and a tailored physical therapy plan. The third stage consists of regular physiotherapy visits and home exercises, with increasing intensity as mobility and strength improve. The fourth stage involves reassessments and a discharge plan, guiding patients to safely return to daily life and continuing long-term exercises to prevent re-injury.

Observations

Some notable observations within the rehabilitation journey are described here.

Unique per patient. Each rehabilitation journey is different, with varying durations and steps, including diagnostic and therapeutic phases.

Communication among healthcare experts. Effective communication and information sharing among healthcare providers are crucial for coordinated care.

Emotional fluctuations. Patients experience emotional ups and downs, with initial hope and later frustration if progress is slow. Small goals can help maintain motivation.

Home-based rehabilitation. Much of rehabilitation occurs at home, which can lead to isolation from work and social activities, affecting their mood.

Impact on family, friends, and work. Rehabilitation affects the patient's support network, requiring more help with daily tasks and emotional support, disrupting routines and work.

Ideation for application smart shirt

The rehabilitation journey helped generate ideas by showing the different stages of recovery and the challenges patients face. Placing ideas along the time line made it easier to understand when and how the smart shirt could be used, and what each moment requires from the design.

It became clear that the shirt could support many applications within the expert interviews, each with different needs. The journey was used to compare ideas and identify which ones are most impact and relevant across multiple stages, and what the requirements from a rehabilitation perspective would be.

Conclusion

The rehabilitation journey map played an important role in both the ideation and evaluation process. It helped identify user needs and challenges, supported the generation of context-specific ideas, and served as a reference for checking if design choices are realistic and relevant.

By using the journey throughout the process, the project stays grounded in the real-life experiences of patients and rehabilitation specialists, making the smart shirt more meaningful and useful in practice.

STAGE 1: INJURY OCCURS

Phase	Touch points	Challenges	Smart shirt possibilities
Triggering event	Initial injury occurs or gets disease. Immediate pain or increasing discomfort signals a problem.	Noticing the injury especially when it slowly changes from a minor discomfort to pain.	Use movement data to prevent injuries by noticing changes, for example by foreseeing fatigue and overload
Initial response	Self-care or ignoring minor pain. Seeking help at GP or er.	Recognising that these symptoms are Significant and deciding to seek medical help.	Enable remote monitoring for users unable to visit the clinic immediately. This could allow doctors to assess severity through recorded data visualized with an avatar.
Diagnosis	Medical examination, diagnosis provided	Communicating symptoms effectively, doctors ability to come to the right diagnosis.	Use for medical examination by measuring exact movements. This data can be used later in the process to show the progress in motion.
Initial treatment plan	Prescription for rest, operation or immobilization, referral to a specialist if needed and explanation of injury recovery	Adhering to the seriousnesses of the injury, but also keeping the advice feasible for the specific patient.	

STAGE 2: RECOVERY AND REHABILITATION

Phase	Touch points	Challenges	Smart shirt possibilities
Acute recovery period	Adherence to rest and treatment, follow-up with doctor for check-ups, monitoring progress or complications	Sticking to rest even when the injury lessens. Effectively communicating progress with the doctor.	Provide users and doctors with periodic updates on upper body motion recovery progress via a connected application.
Referral	Referral to a rehabilitation centre if mobility or strength is significantly affected	Assessing the seriousness of the injury and correctly and referring to the appropriate and fitting doctor or physiotherapist	
Initial assessment physiotherapy	Detailed evaluation of injury, mobility, pain levels, and overall physical health. Setting clear rehabilitation goals.	Clearly communicating the injury and managing expectations of the patient. Accepting the treatment plan and the road ahead.	Visualise limitations in range of motion on the avatar.
Creating a rehabilitation plan	Exercises to improve mobility, flexibility, and strength. Gradual progression of load and intensity to match recovery stages.	Making a treatment plan which fits with the patients injury, his character and daily life.	Enable physiotherapists to set recovery milestones and goals that are visualised on the avatar.

STAGE 3: PHYSIOTHERAPY SESSIONS

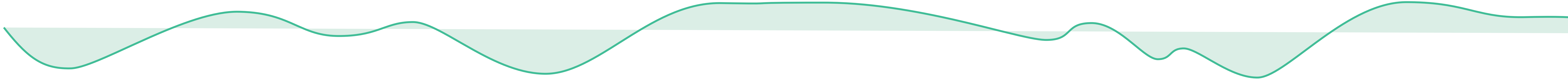
Phase	Touch points	Challenges	Smart shirt possibilities
Physiotherapy visits	Regular sessions, guided exercises, manual therapy, and use of equipment.	Making time for regular physiotherapy sessions. Handling irritation and disappointment when simple exercises are difficult.	Incorporate user input about pain levels into the visualisation, helping correlate movement patterns with discomfort.
Monitoring progress	Tracking improvements in mobility, pain levels, and strength. Adjusting the rehabilitation plan as needed.	Assessing improvement correctly for each patient.	Track changes over time in the movement data.
Home exercises	Instruction on exercises to perform independently. Encouragement to maintain consistency and follow routines.	Remembering exercises correctly, staying motivated, and remote monitoring based on patient reports.	Provide real-time feedback during physiotherapy exercises to ensure correct form and technique. Use the avatar to demonstrate ideal movements and compare them with live user data to highlight differences. Use the avatar in a game to motivate the user to follow the exercise plan and to fully and correctly perform the exercises. Show progression or scores to the user to keep the motivated. Show physiotherapists the movement data so they can assess the progress objectively. Enable physiotherapists to share recorded sessions and data visualizations with users, making progress easy to understand and more tangible.
Adding weight to exercises	Addition of weights to exercises or/and increasing intensity to improve reach and muscle strength.	Recognising when patient is ready for next step in rehabilitation process.	
Goal specific exercises	Instruction on exercises specific to sport, work or daily life of the patient.	Recognising when patient is ready for next step in rehabilitation process.	

STAGE 4: RETURN TO NORMAL FUNCTIONING

Phase	Touch points	Challenges	Smart shirt possibilities
Reassessments	Final evaluations to assess functional recovery. Testing strength, mobility, and endurance in real-life scenarios.	Reassessing the patient at the right moment.	Simulate movements problematic activities with avatar and evaluate readiness to return. Provide "readiness scores" based on data, giving users and stakeholders confidence in the recovery.
Discharge plan	When fully recovered, the physiotherapist provides a discharge plan with advice on prevention	Reassuring patients of their recovery and informing them on what to expect when going back to normal.	Enable users to continue exercises at home with real-time feedback. Detect and warn about risky movements that could lead to re-injury.
Long-term maintenance	Continuing exercises for strength and flexibility to prevent re-injury. Periodic check-ins if there are lingering issues.	Adhere to prevention plan, even when pain at the moment. Immediately going to physiotherapist when re-injury occurs.	Enable users to see improvements since the initial injury, reinforcing positive habits.

Time: from same day up to months · 30 minutes · dependent on diagnosis · 30 minutes · 30 minutes, 2 times a week · during visits · everyday until discharge, dependent on diagnosis · 30 minutes · during final meeting · rest of patients life

Emotions:



People: family & work · GP/ER/other doctors · rehabilitation doctor · specialist · family & friends · physiotherapist · family, friends & work · physiotherapist · family, friends & work

Figure 24. *Rehabilitation journey*

5.3. Current tools & methods in rehabilitation

Although physiotherapists and rehabilitation doctors often rely on visual assessments, as revealed in expert interviews, they use tools to systematically document, objectify, and compare patient assessments. These tools are vital for making informed decisions, monitoring progress, and tailoring patient care. A variety of tools and methods are currently used to create a comprehensive understanding of a patient's condition.

Given that the smart shirt would be valuable only if it introduces new capabilities or enhances existing tools and methods, it's crucial to have a clear insight into the current tools.

The following questions will be researched:

What are the current limitations and gaps in the tools and methods used?

How do these tools measure up in terms of objectivity and subjectivity?

What tools are missing?

What types of data do they produce?

Where could a smart shirt add value?

Exploring these questions will help decide the smart shirt's potential role and value, ensuring its development is strategically aligned with enhancing rehabilitation practices.

Overview

With information from the discover phase, a comprehensive overview of the current tools and methods used in rehabilitation has been developed. Figure 25 presents frequently used tools and methods and provides a brief explanation of their function. The tools are categorised based on what they measure. They are also grouped depending on other criteria: the targeted body part, whether they are diagnostic or therapeutic tools, and whether the measurements they provide are objective or subjective (see Figure 26). This exposes new insights of the tools and methods available in rehabilitation. For a detailed breakdown of these categorisations, see Appendix F.

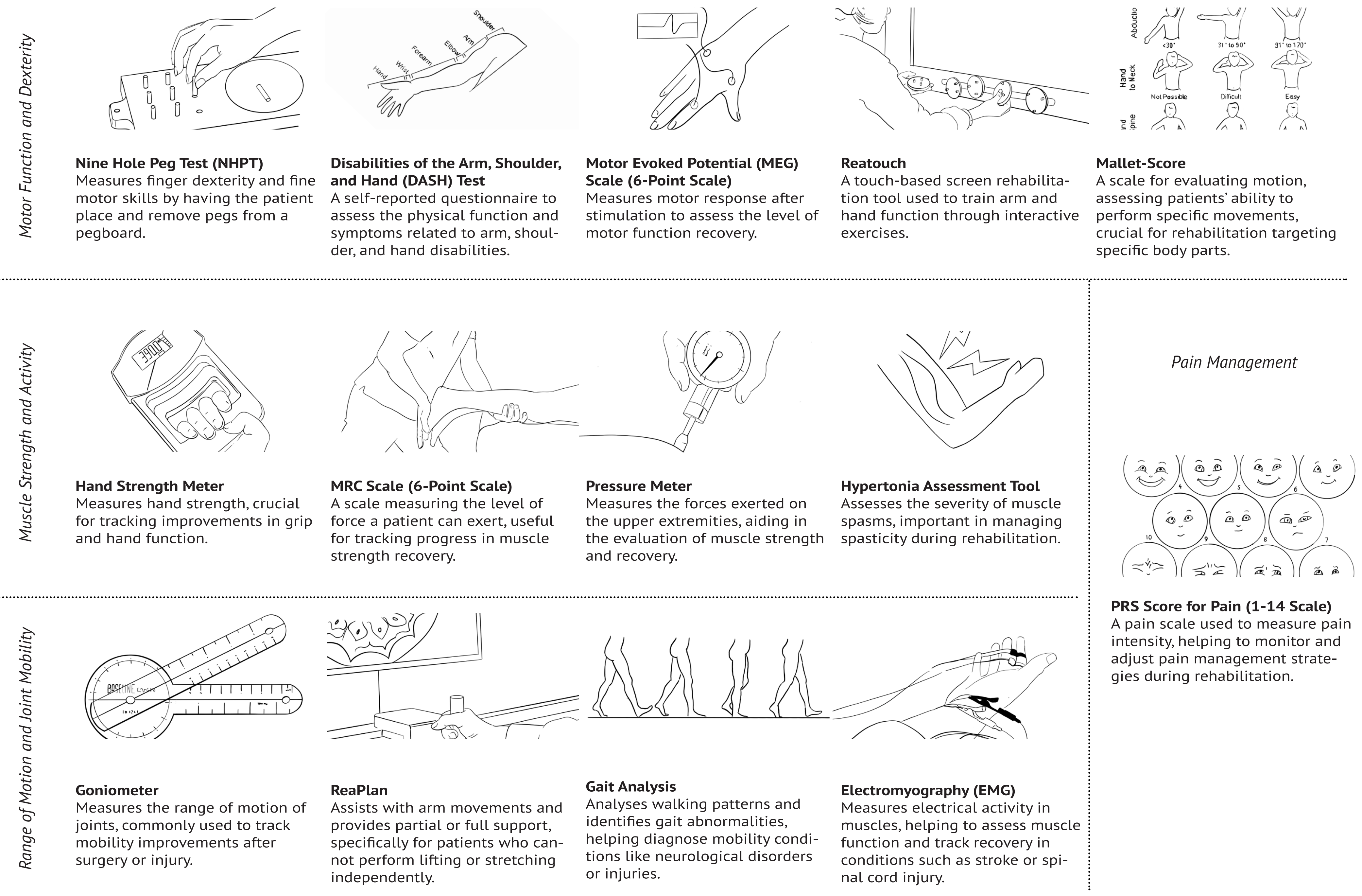


Figure 25. *Current tools and methods used in rehabilitation*

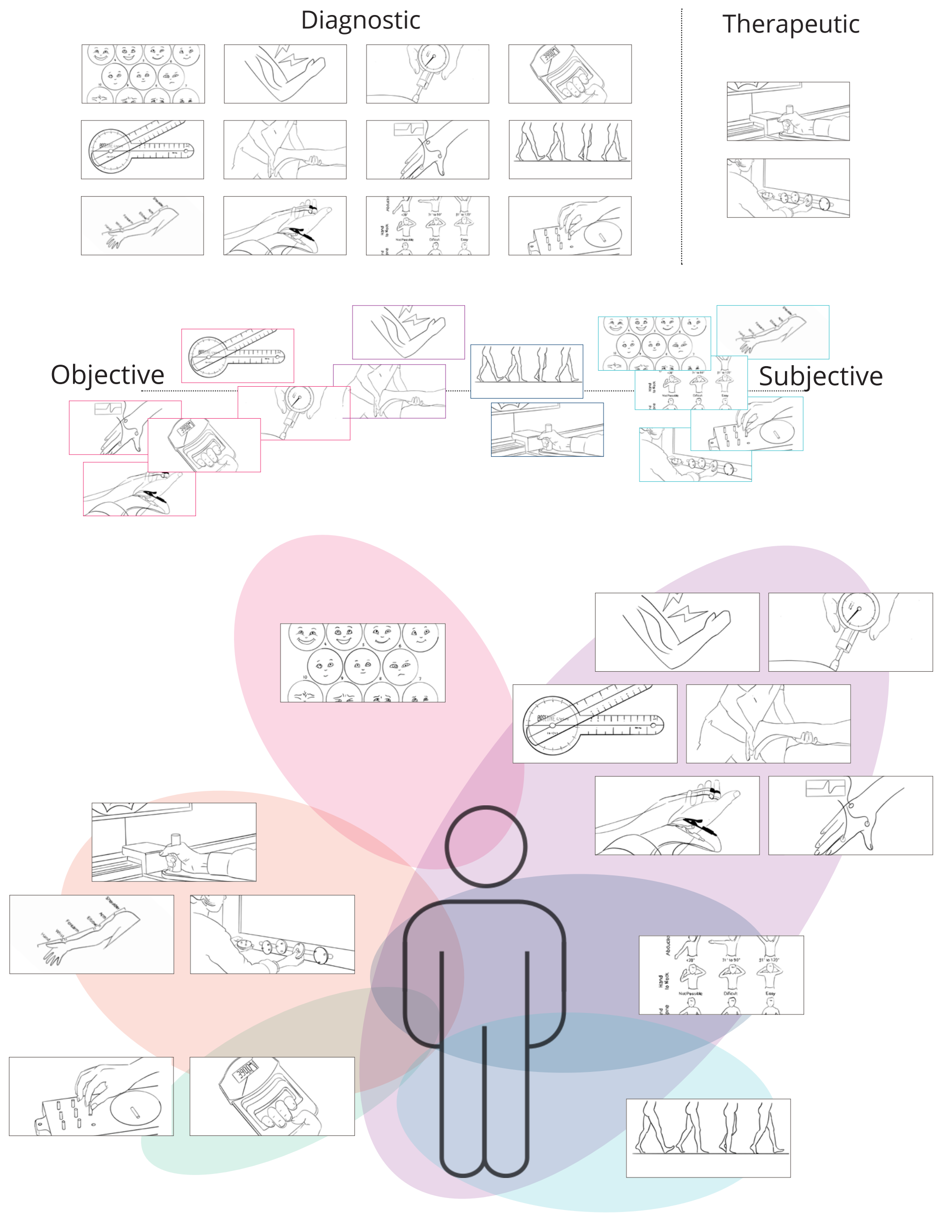


Figure 26. *Current tools and methods arranged with different criteria: body part, diagnostic versus therapeutic and object to subjective tools*

Insights
Rehabilitation tools often focus on a specific body part or function, measuring one aspect at a time. Tools for the upper body, like those for hands and arms, assess these areas separately, not as a cohesive whole. Most of these tools also tend to provide just numerical scores, with gait analysis being a notable exception that visually represents movement. Tools are predominantly focused on diagnosis, only a select few tools such as ReaPlan and React are designed for therapeutic use. Moreover, many tools involve a subjective element, relying on either self-assessment or the expert's interpretation. Additionally, their use is generally limited to clinical settings under medical supervision. There is a need for more integrated and versatile rehabilitation tools that can be used effectively outside traditional clinical environments.

Conclusion
The insights from the current tools analysis inform the smart shirt's design on what direction to choose for the future application. By using motion capture for the entire upper body's movements, it could offer a more holistic view than current tools. Integrating visual feedback could also enhance understanding and interpretation of movement data, making the shirt more user-friendly. Moreover, incorporating objective measurement technologies in the smart shirt can help reduce the subjective nature of traditional assessments. Above all, the therapeutic tool proposed in the expert interviews would add significant value, especially for home use, as there are very few therapeutic tools available for use at home.

Key Takeaways

Physical context
- The shirt must be robust to withstand daily use by patients.
- The shirt must be intuitively and simple to use, so a patient can use it independently.
- The shirt should work with common devices and have a charging solution compatible with standard plugs. The shirt should be compatible with existing rehab devices to integrate seamlessly into group activities like walking or motion classes.

Rehabilitation journey
- The rehabilitation journey generally has four stages: injury, acute recovery, regular rehabilitation, and long-term maintenance.
- Each rehabilitation journey is different, with varying durations and steps, including diagnostic and therapeutic phases.
- Rehabilitation affects the patient's support network, requiring more help with daily tasks and emotional support, disrupting routines and work.
- Effective communication and information sharing among healthcare providers are crucial for coordinated care.
- Patients experience emotional ups and downs, with initial hope and later frustration if progress is slow. Small goals can help maintain motivation.

Current tools and methods
- Rehabilitation tools often focus on a specific body part and measure one aspect at a time.
- Most of the tools provide just numerical scores and are focused on the diagnosing part of the process. Most tools have a subjective element in them.
- There are many diagnostic tools, but less therapeutic ones.

Figure 27. *Sewing straight ahead*

6. Specifying the design direction

This chapter narrows down the project from many possible directions to one clear design aim. Attention goes to the future applications, the essential functions of the smart shirt and their corresponding requirements.

6.1. Design scope

The scope, illustrated in Figure 28, defines the boundaries of the project. This project develops a proof of concept for a smart shirt that uses IMU-based motion capture to visualise rehabilitation movements in real time. It does not aim to deliver a market-ready product, but instead investigates how wearable motion tracking can be meaningfully integrated into textiles to support long-term recovery at home.

The shirt is designed for rehabilitation patients who are open to new technologies, as well as their rehabilitation specialist. The focus lies on seamless integration of the electronics, wearer comfort, and the making of the movement visualisation. While the visualisation application is taken into account, its development falls outside the scope of the prototype. The aesthetic of the shirt itself is considered, but the aesthetics of the visual output are not.

The technical setup uses five BNO055 IMUs and conductive thread. The sensor choice was made in a previous project and not reconsidered. This project focuses on using pre-made components rather than developing custom PCBs.

Several aspects are intentionally left out of scope, including user testing with patients, market-readiness topics such as scalability or washability, and broader sustainability strategies. Only the separation of electronics and textile at the end of life is addressed, as it relates directly to the integration method.

This scope sets the initial direction for development, while remaining open to additional elements that may emerge.

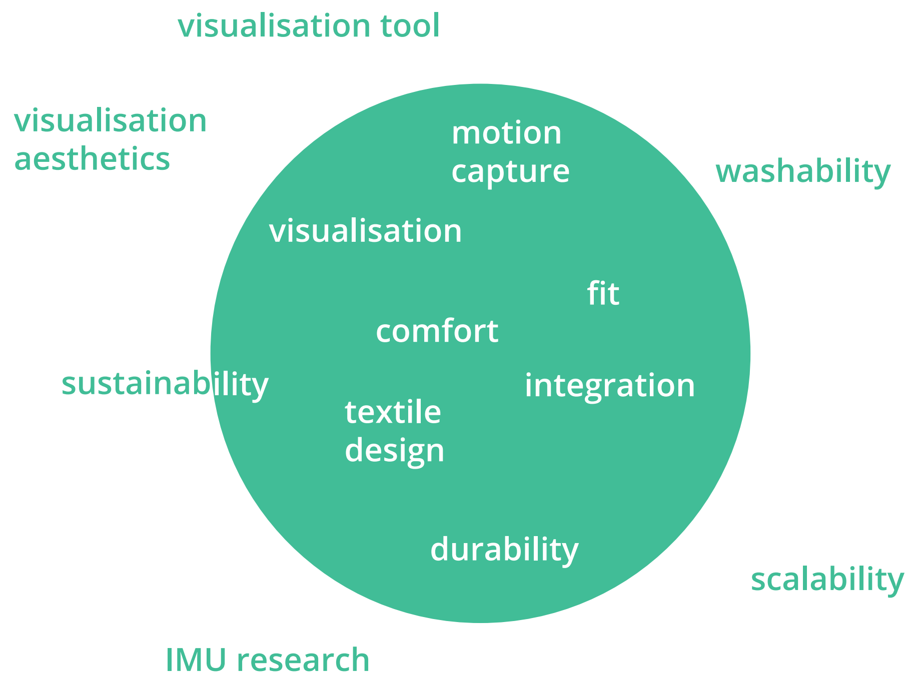


Figure 28. *Project scope*

6.2. Target group

This project focuses on two main user groups: rehabilitation patients and their rehabilitation specialists. Understanding their needs, limitations, relation and roles helps shape the design and informs key design decisions.

Patients
The shirt is intended for rehabilitation patients recovering from upper-body impairments. They have difficulty with executing simple arm movements due to their condition. Most patients are highly motivated to improve, but they have a strict physical therapy plan to adhere to. Lack of motivation, time or understanding of the exercises is common.

The targeted patient in this project is affected at one arm, which is most common according to rehabilitation experts. They are physically and cognitively capable of performing daily exercises without continuous supervision. Patients with severe motor precision issues or cognitive impairments are outside the scope of this concept, as they may require specialised assistance or more adaptive tools. They can operate a basic smartphone, and are capable of understanding visual feedback to adjust their movements. Their physical performance may be limited by reduced range of motion, compensatory movement patterns, or jerky execution, often seen in neurological rehabilitation. The goal of the targeted patient is to regain independence and confidence in practical tasks. This entails tasks as folding laundry, lifting a child, or going back to work.

The patient is between the 18 and 65 years old, has a small or medium shirt size. For practical reasons, the focus will primarily be on sizing for women.

Figure 29. *Target group: the patient and their rehabilitation physiotherapist*

Rehabilitation Specialists
The target rehabilitation specialists in this project are rehabilitation doctors and physiotherapists, who monitor patient progress and guide therapy plans. They treat many patients at once, which increases time pressure and requires them to tailor treatments to each individual's recovery process.

These specialists primarily rely on observation as a diagnostic tool, using their expertise to assess movement quality and detect compensatory behaviours. They are familiar with tools like React and Reaplan, and are generally open to adopting new technologies that improve efficiency, enhance care quality, help prevent pain, and accelerate rehabilitation progress. They value clear and easy to understand visualisations particularly for understanding how patients perform exercises at home, where direct observation is not possible.

6.3. Different smart shirt applications

The smart shirt design, motion capture system, and visualisation must be adaptable to a range of future applications within rehabilitation. The discovery phase revealed several promising directions for the shirt and revealed the preference for a therapeutic tool. The main envisioned therapeutic implementations are illustrated in Figure 30. The final design should be adjustable to these applications in the future.

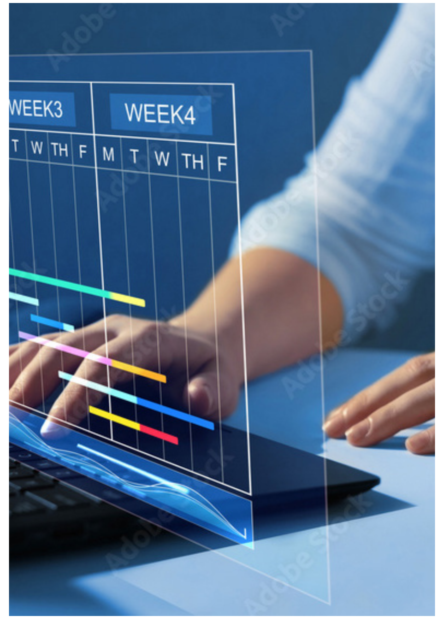
Figure 30. *Different future applications of the smart shirt*

Home insight
The shirt could provide re-habilitation specialists with a clearer understanding of how patients move at home and how well they perform their prescribed exercises.

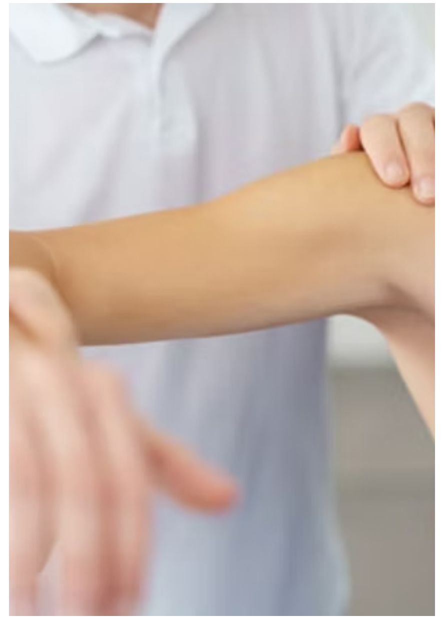
Motivation tool
By making exercises more fun and interactive, the shirt could help motivate patients to stay engaged and consistent in their rehabilitation routines.

Exercise leading tool
The system could guide pa-tients through their exercises, offering real-time feedback and structure. This would help them perform movements correctly and build confidence in their recovery process.

Explanation tool
Rehabilitation professionals could use the visualisations to explain proper movement techniques and provide tar-geted feedback on how the patient is performing specific exercises.



Visual progress tool
By saving and comparing visualised movements over time, the system can track progress and support hand-over between rehabilitation specialists.



Biofeedback tool
By integrating haptic, sound or light based feedback next to the IMUs, the smart shirt could be used for error-less learning.

6.4. Smart shirt functions

To develop a design capable of motion capture and visualisation, the necessary functions of the smart shirt were noted down. A Function Analysis (Delft Design Guide, 2021) was used to identify and organise all main and supporting functions. Figure 31 presents the outcome of this analysis. Functions are structured top to bottom in chronological order, and from left to right from main to sub-functions. In the final step, only the functions within the project scope are depicted, defining the essential functions the smart shirt must fulfil.

Figure 31. *Function diagram*

PREPARE FOR MOTION CAPTURE

Give structure
- Allow user to put shirt on
- Hold all parts in their correct place

Power & communicate
- Supply power
  - *Put power on & off*
  - *Charge*
- Establish stable communication between all parts

Prepare motion capture set up
- Start visualisation tool
- Allow manual or automatic calibration

CAPTURE MOTION

Collect data
- Detect upper body movements
- Measure raw IMU data
- Collect IMU measurements

Process data
- Fuse raw IMU data into rotational data

Transmit data
- Transmit data to an external device
- Enable real-time streaming of rotational data

Manage data
- Store collected data temporarily for processing

PROCESS MOTION CAPTURE

Visualise data
- Display user upper body characteristics
- Use rotational data to calculate upper body movements
- Display user upper body movements visually

Give user feedback
- Provide real-time feedback on posture or movements

Design requirements

Design criteria were made according to method List of Requirements (Delft Design Guide, 2021). These criteria were defined based on insights from the discover and define phase, focusing on the most important findings. The requirements were defined to provide a framework for making design choices in the development phase and for evaluating the final design.

Base shirt design
1. Stretch: Incorporate stretchable materials to provide a snug fit for accurate sensor readings
2. Fit. Accommodate women with sport shirt size Small and Medium.
3. Robustness. Ensure the shirt can withstand repeated wear and maintain its integrity through physical activity.
4. Weight & bulk. Keep the shirt as lightweight as possible and the components as small as possible to maintain comfort and usability during daily wear.
5. Unobstructiveness. Ensure that the shirt allows for natural movement without restricting mobility.

Integration of electronic components

6. Electronic parts choices. Use standardised electronics and BNO055 IMUs for the smart shirt.

7. IMU placement. Position 5 IMUs on the upper body, one on the back, one on each upper arm and lower arm, to provide motion data on each significant upper body part. Place the IMUs on bony parts to prevent influence of muscle contractions on the motion data.

8. IMU stability. Secure each IMU tightly against the skin using appropriate fastening methods to prevent displacement or shifting during movement.

9. Wiring. Use flexible, strain-resistant, conductive thread to accommodate movement and reduce the risk of breakage.

10. Transition zones. Reinforce transition points between soft textiles and hard electronics to minimise stress and prevent failure.

Motion capture & Visualisation

11. Collecting data. Collect IMU data for a practice session of 30 minutes long.

12. Visualisation content. Generate a stick figure representing the upper body mirroring the patient's movements in real-time.

13. Accuracy. Ensure that the system visualises user movements in real time with such high fidelity that a trained expert cannot visually distinguish the rendered motion from the actual physical movement. Above all, the visualisation must be accurate enough to be used for a therapeutic tool.

14. Minimal calibration. Use a calibration method which can be accurately performed by the user group, patients in rehabilitation, without help of an expert. Do not use pose calibration.

15. Understandable. Clearly show the user's movements in real time with a simple and intuitive design, understood by both patients and experts without additional explanations.

User interaction

16. Pulling on & of. Ensure the shirt can be put on and taken of by the patient themselves, and with one functional arm.

17. Adjustments. Minimize the need for user adjustments to achieve correct sensor placement; the shirt should naturally guide IMUs into accurate positions with minimal manual correction.

18. Autonomy & set up: No expert is needed to set up the motion capture system and visualisation. The patient needs to be able to start measuring within 3 minutes time.

19. Charging. The shirt can be fully charged in 10 minutes time by the patient at home or the expert in the clinic with a standardised charging method.

Aesthetics

20. Discreet appearance. Ensure the design is visually appealing for a broad target group and encouraging use in social or public settings.

Safety

21. Battery Safety. Ensure secure housing or immediate removal for batteries to prevent accidents.

Future-Proofing & desirability

22. Upgradeability. Design the shirt to accommodate potential future upgrades for different applications.

23. Low cost. Cost less than 500 Euro to fabricate the smart shirt.

Sustainability

24. Separability. At end-of-life the electronics and textile parts should be able to be separated for recycling in the least steps.

25. Repairability. Parts should be able to be replaced or repaired when needed to extent the life time of the shirt.

Phase C

Develop

The develop phase is all about developing ideas and concepts, prototyping, testing, choosing specific solutions and combining them to come to a final design concept. This phase describes and shows the different design steps and explains the choices that were made towards the design concept.

This phase entails the following chapters:

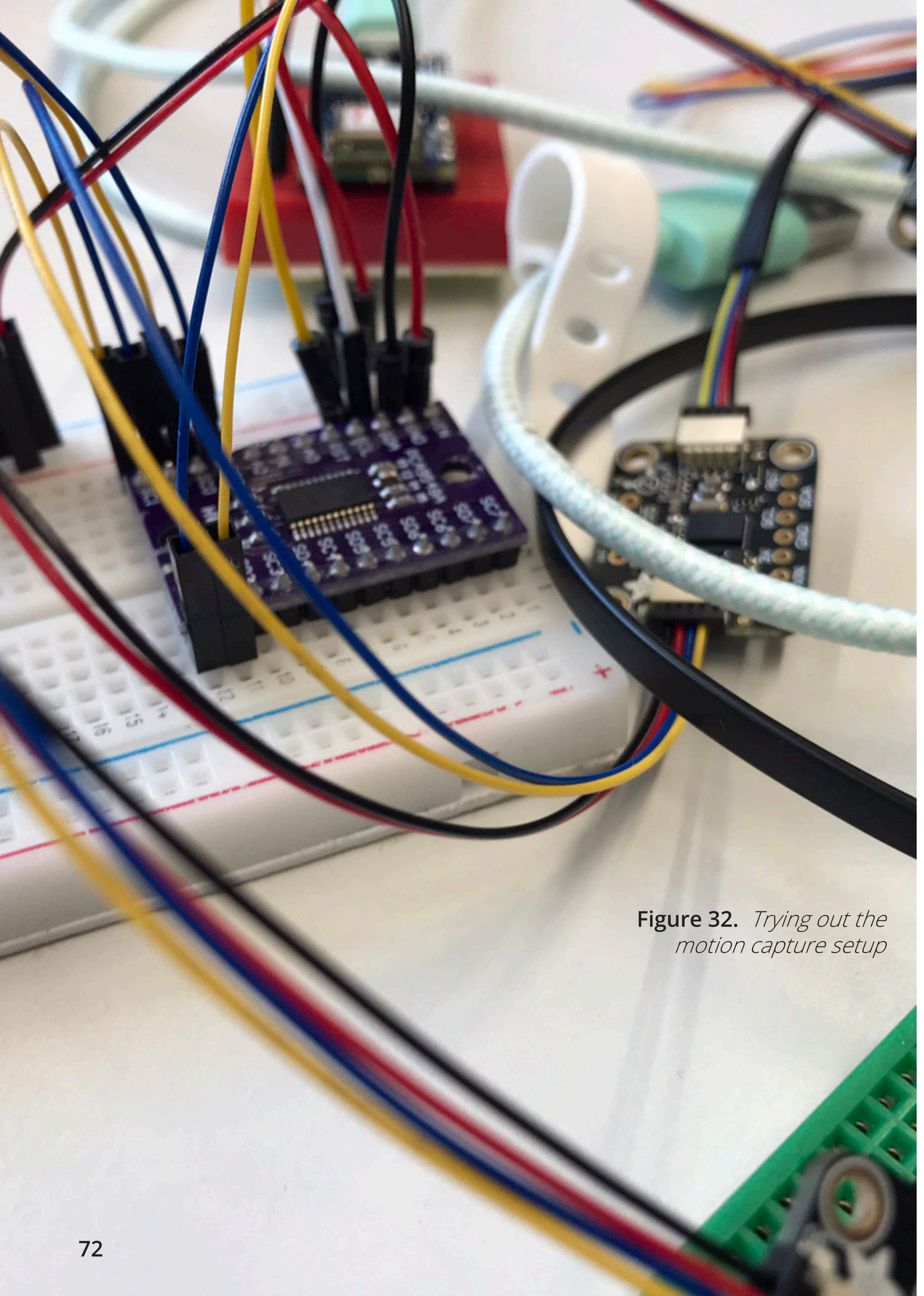


Figure 32. *Trying out the motion capture setup*

7. Visualisation of motion capture

The most essential function of the smart shirt is going from human upper body movements to movement data to visualisation. Therefore the development was started by exploring motion capture. It can be divided in the hardware set up, gathering rotational data from IMUs and visualising this data. In this chapter the exploration and further development of these steps is described.

7.1. Gathering rotational data

For this project, the BNO055 IMU was selected due to its integrated sensor fusion technology, combining data from the accelerometer, gyroscope, and magnetometer to provide accurate orientation readings with minimal processing. It is compact and reasonably priced at 28.49 Euros. The BNO055 was recommended during the interview by Alamel et al. (2024) and used in the Acans smart suit as well.

An initial setup was created to get familiar with IMU-based motion capture. The circuit, shown in Figure 30, connected BNO055 sensors through a multiplexer to an Arduino Nano. The Grove 8 Channel I2C Hub TCA9548A multiplexer was used to switch between sensors, as all BNO055s share the same default address. This setup allowed data collection and visualisation, though extending the IMU wires to the wrists caused signal degradation. Signal amplifiers were added to ensure reliable data transmission.

Quaternions were chosen for data acquisition instead of Euler angles. Euler angles suffer from gimbal lock (see Figure 34), making quaternions a more stable choice for 3D orientation data. Arduino IDE was used to develop the acquisition code (full code in Appendix M).

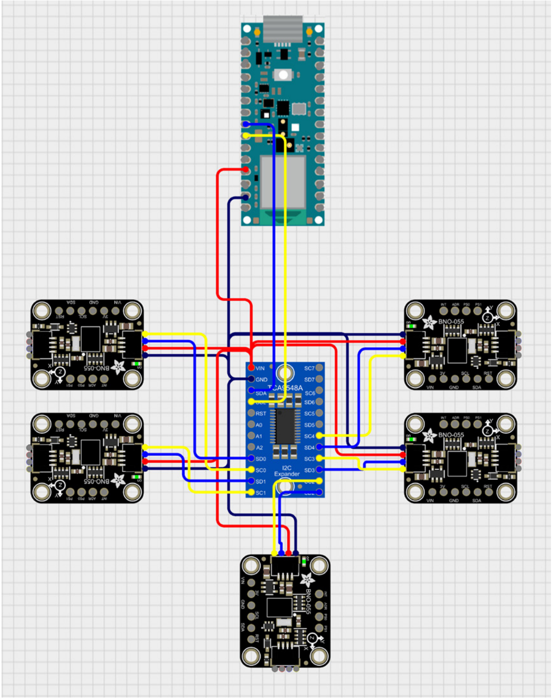


Figure 33. *First set up of electronics for motion capture with the smart shirt*

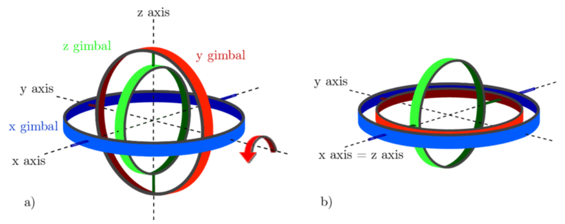


Figure 34. *Gimbal lock*

7.2. Visualisation of movement data

To visualize rotational data, a pre-existing tool was chosen, as the project doesn't focus on software development. Both OpenSense and Blender, discussed in section 3.3 IMU-based motion capture , were tested with the initial electronic setup to find the best fit for visualizing upper body movements from the smart shirt.

OpenSim prototype
A prototype was developed using OpenSense, with the aim of exploring the available features and identifying potential challenges within the software.

Figure 35 shows a flow diagram of the setup used in OpenSim. First, the Rajagopal2015 model is scaled to match the subject's dimensions. IMU data is collected from the serial monitor and used to calibrate the model with the IMU Placer. Motion data for inverse kinematics is then gathered, processed through the IMU IK tool, and refined for detailed kinematic data. Finally, the results are opened and analysed in OpenSim.

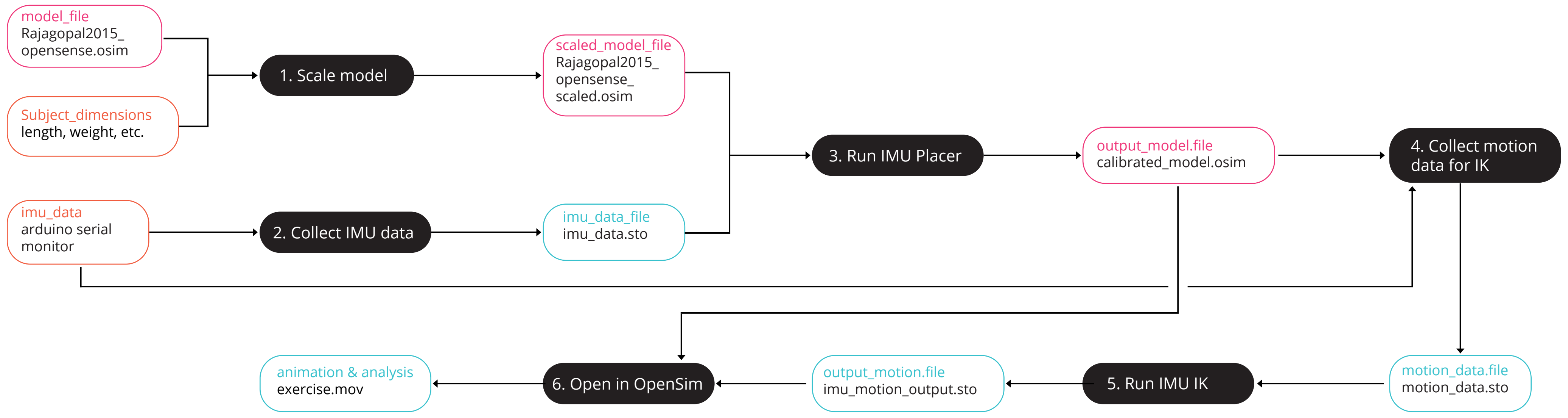


Figure 35. *Flow diagram of OpenSim setup*

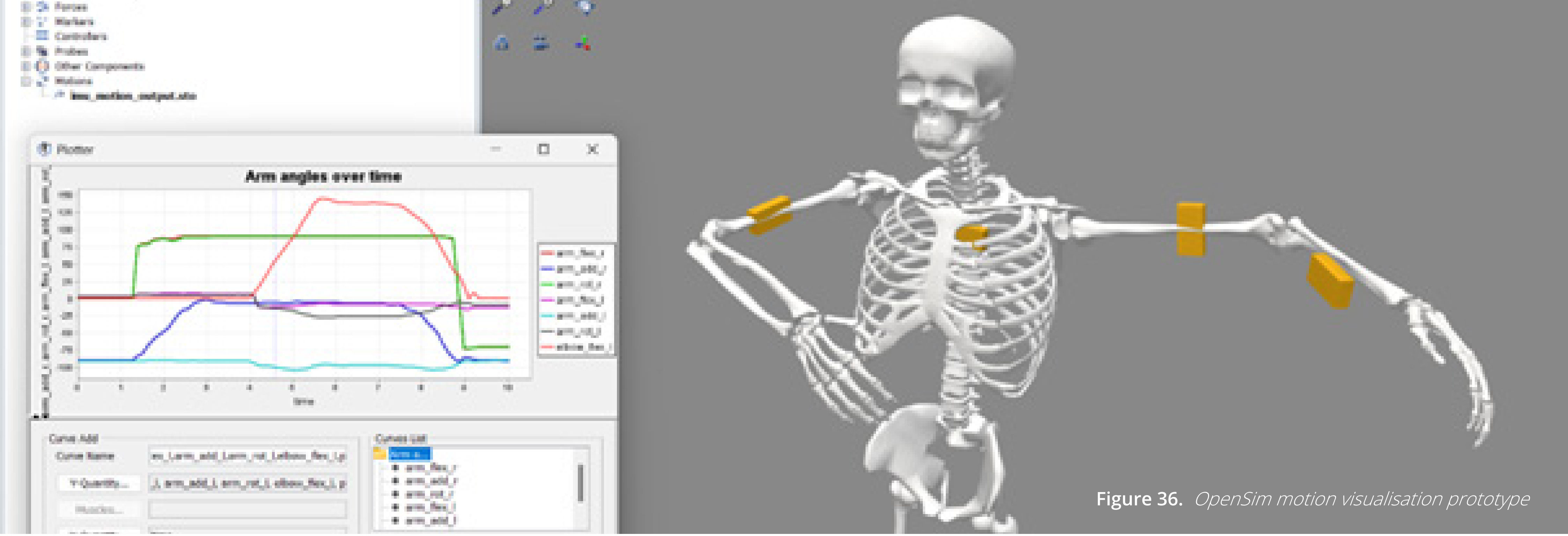


Figure 36. *OpenSim motion visualisation prototype*

Figure 36 depicts a screen shot of the OpenSim output, the actual output is an animation. The prototype demonstrated that OpenSim works efficiently and provides a wide range of functions. It allows for precise IMU placement, the models already incorporate detailed human body characteristics and a pose calibration method. Additionally, OpenSim can generate tables and graphs for further analysis of the saved motion data.

However, an attempt to create a real-time visualisation was unsuccessful. OpenSim is not typically designed for real-time visualisations. This can not be implemented within the standard OpenSim interface, but needs extensive knowledge of the OpenSense software and advanced programming skills.

Blender prototype
The focus of the Blender prototype was on achieving real-time visualisation, a feature not achieved in OpenSim. In Blender an armature was made with a simplified bone set up. A Python script reads the quaternion data from the serial port and applies the rotations on corresponding bones in the simplified model's armature in real-time.

The system operates smoothly, allowing easy adjustments to the visualisation. Unlike human movements, the model can move in all directions, presenting no issues for this application when someone puts the shirt on. However, the system experiences occasional glitches, such as the torso turning upside down at the end of Blender's time line. Furthermore,

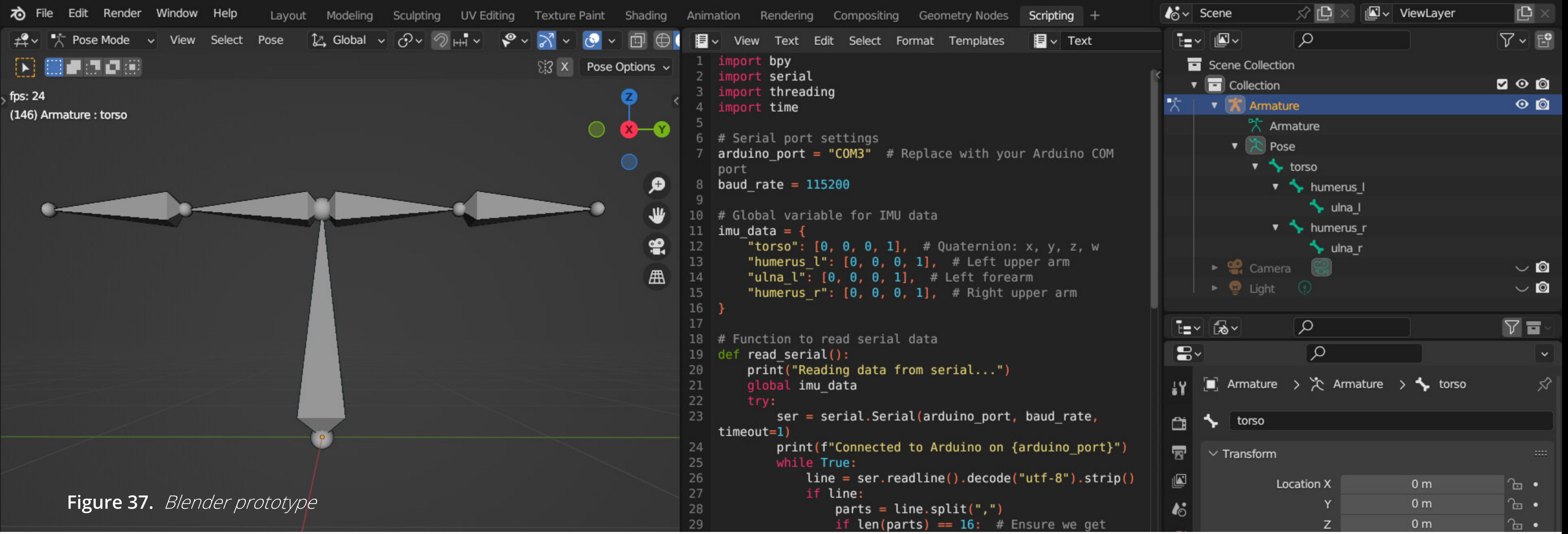


Figure 37. *Blender prototype*

calibration has not yet been implemented and is needed to compensate for the placement of the IMUs on the body. Finally, the visualisation gives a quite abstract representation of the upper body.

Visualisation program choice
A Harris profile (Delft Design Guide, 2021) was used to choose the visualization tool, as shown in Figure 38. The Blender prototype was selected because real-time visualization was a key goal (1.4 Goals & criteria). Blender offers flexibility with coding and visualisation adjustments, which OpenSim lacks. OpenSim requires pose calibration, not suitable for the target group. The medical insights from OpenSim are less relevant, because the shirt has more therapeutic purposes.

	OpenSim				Blender			
	--	-	+	++	--	-	+	++
Real-time visualis-ation	■							■
Adjustability to future applications	■							■
Calibration options		■					■	
Stability				■		■		
Accuracy			■				■	
Understandable			■			■		

Figure 38. *Harris profile: OpenSim versus Blender*

Design concept: motion capture & visualisation

For the final concept the electronics set up is adjusted in the following way.

Xiao nRF52840 Sense. The Arduino Nano is swapped for a smaller Seeed Studio Xiao nRF52840 Sense module, which included a Bluetooth module. This reduction in size, by approximately half, coupled with the wireless capabilities of the Bluetooth module, significantly increases the practicality of the shirt by eliminating the need for a wired connection to the computer and allowing greater freedom of movement for the user.

PKCell 150mAh 3.7V. The power supply a PKCell 150mAh 3.7V battery, capable of powering the shirt for at least 30 minutes is selected, essential for practical use with a wireless setup. This battery was also chosen for its ability to be recharged directly through the Xiao module, simplifying the usability.

IMUs in series. To further reduce the complexity of wiring, the IMUs on the arms will be configured in series. There is chosen to use IMUs with Stemma QT connectors, which does increase the height with 3 millimetre compared to soldered on connections. However, the connectors keep the set up flexible. Moreover, they can endure bending close to the connection point better than soldered on wires.

For the final visualisation an updated version of the blender prototype will be used. The following updates will be made.

Adding shoulders. To make the armature more representable of the human body, shoulders must be add in. They must be fixed directly to the top of the torso. This also helps with recognising which side of the armature you are looking at.

Wireless connection. A wireless connection needs to be set up with in the visualisation, because then the USB-C wire connecting the shirt with the computer can be removed. This will give the user more movement freedom, which will benefit the experience and the actual use cases the shirt could applied for.

Adjustments for starting position of IMUs. A form of calibration should be added to the motion capture flow. To adjust the rotational data for the begin position of the user and the placement on the body.

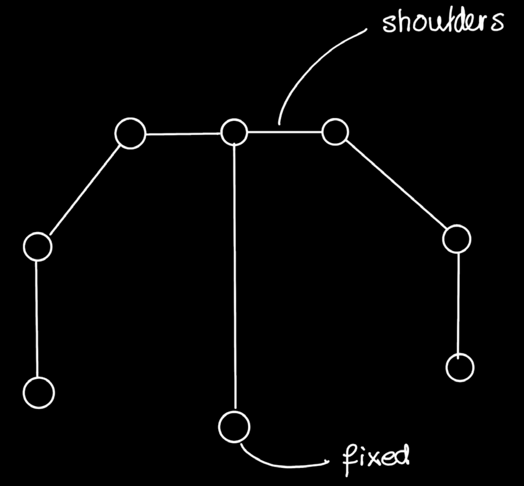


Figure 39. *IMU integration on upper arm*

8. Integration of IMUs

This chapter delves into the technical challenges and solutions associated with integrating the IMUs on the arms into the shirt, focusing on wearer comfort, optimal sensor placement, and their influence on capturing movement accurately. The analysis is divided into two main sections: the first addresses the integration of the IMUs on the arms, discussing optimal placement strategies, embedding these sensors within the shirt fabric. The second addresses methods to prevent sensor displacement during exercises.

8.1. Placement of IMUs on arms

The correct placement of the IMUs on the arms is critical for accurate motion capture. One IMU must be placed on the upper arm, the other on the lower arm. The requirements for the placement of IMUs are:

- Position on bone rather than muscle
- Ensure comfort for each individual
- Do not impede with the normal movements of user

UPPER ARM

The upper arm offers several placement options: front, side, or back, and either low or high on the arm. The chosen placement is high on the back of the upper arm, similar to where diabetes management devices are placed, which is proven to be the most comfortable for long-term wear. This position also ensures the sensor stays on bone rather than muscle, ensuring reliable motion capture data.

LOWER ARM

For the lower arm, sensors can be placed near the wrist or elbow, and on the inside or outside. The chosen placement is on the outside of the wrist, which is commonly used in literature (see 3.3 IMU-based motion capture). This position captures hand rotations better than near the elbow, which has more muscle activity. Placing the sensor closer to the elbow is avoided, as variable arm lengths may cause incorrect positioning, leading to inaccurate data. The outside of the wrist offers a flat, wide surface for the IMU.

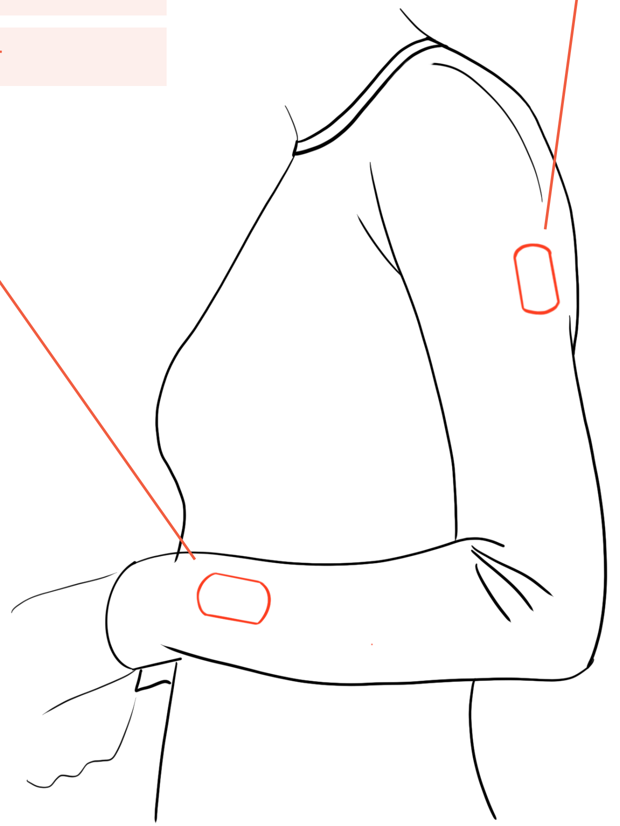


Figure 40. *IMU placement on the arms*

8.2. IMU Integration

This section outlines the methods explored for attaching IMUs to the shirt and details the chosen method based on the criteria from the List of requirements. The most important criteria were comfort, sensor stability, durability and being separable.

Drawing ideas was the first step of ideation the results can be seen in Appendix B.

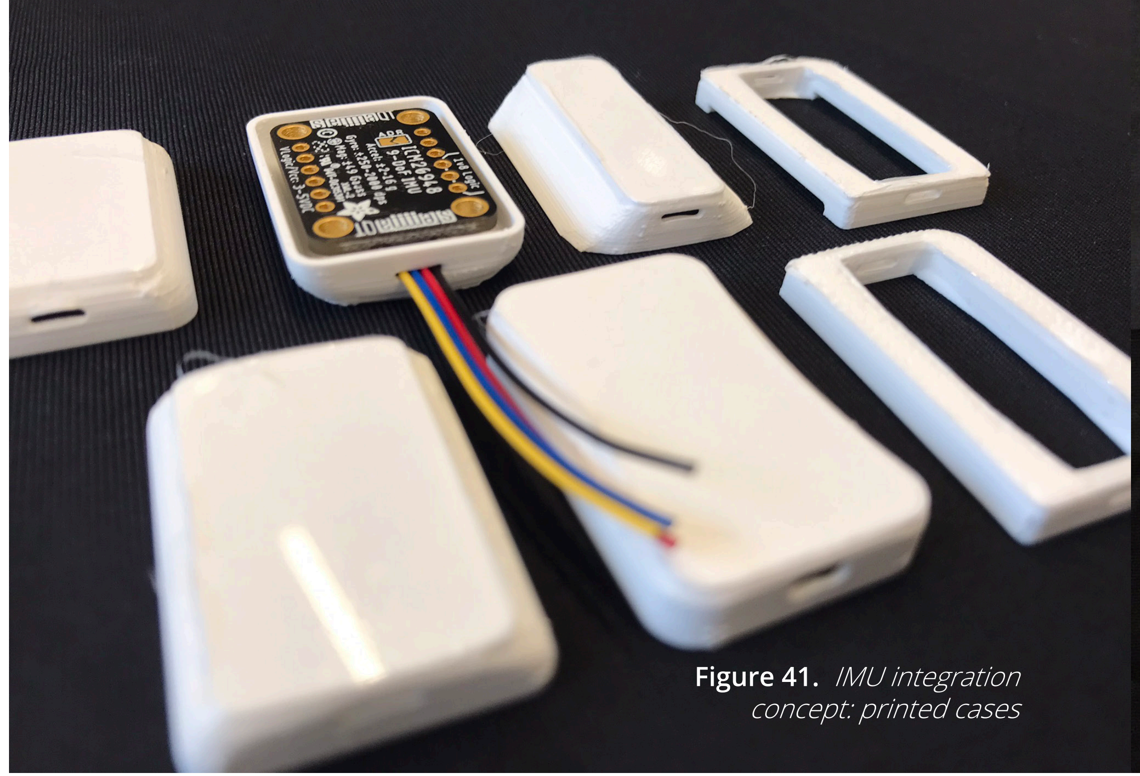


Figure 41. *IMU integration concept: printed cases*

Figure 42. *IMU integration concept: Closed and open textile pocket*

Prototypes
The most promising solution identified was the use of textile pockets. This method adds minimal material bulk, thus maintaining the shirt's lightweight nature, and uses soft fabrics to enhance comfort and ensure seamless integration with the wearer's movements. Various pocket configurations were made to find the ultimate textile pocket.

TEXTILE POCKETS WITH HARD CASES

These pockets include hard cases to protect the IMUs against damage and ensure secure placement of connectors. While this enhances the durability of the sensors, it adds bulk, hard elements to the shirt. Particularly at the transitions from soft to hard materials, which could affect comfort and vulnerability.

This concept also prevents the connectors from being pulled out, this will be discussed in 10.3 Integration of the conductive wire.

CLOSED TEXTILE POCKETS

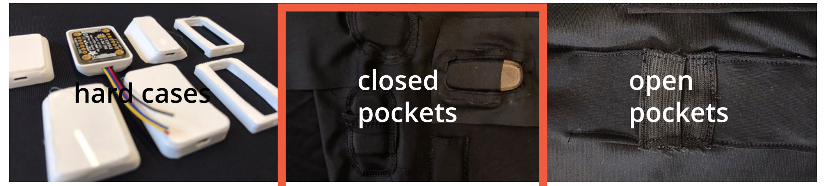
By fully enclosing the IMUs, these pockets offer better security and protection. They can be made very small and tight, which improves comfort and data reliability from the sensors. The simplicity of the design is a major benefit. However, the major downside is the difficulty in removing IMUs for maintenance or washing, as they would need to be washed along with the garment.

OPEN TEXTILE POCKETS

These pockets allow for easy insertion and removal of the IMUs, facilitating maintenance and the separation of electronics from textiles at the end of their life cycle, which is essential for recycling. This design also enables a model where shirts can be purchased by patients in sizes that fit them, while sensors can be provided by rehabilitation clinics. This can help to keep costs low for patients. However, these pockets are more complex and require more material than closed pockets, as they involve multiple layers. There's a higher risk of sensor movement within the pocket, which could make rotational data less reliable. Additionally, many patients may not have the expertise required to manage the electronics themselves, increasing the risk of damage during assembly and disassembly.

IMU integration choice
The decision was made to use closed textile pockets, based on the Harris profile (see Figure 43). These pockets are more comfortable due to fewer hard parts and are simpler and smaller. However, they leave the electronics more exposed which makes them less durable..

To improve durability, sturdier elastic material from the open pocket concept was used. This protects the sensors from impacts. It also helps keep the connectors securely attached by slightly stretching the elastic over the sensor during sewing. Once released, the elastic keeps the connectors in place. An iron-on fabric reinforcement is applied under the sensor to provide a stable base and reduce bending between the soft fabric and hard electronics.



	hard cases				closed pockets				open pockets			
	--	-	+	++	--	-	+	++	--	-	+	++
Comfort	■							■				■
Durability			■			■				■		
Sensor stability	■							■			■	
Size	■							■			■	
Separability				■				■				■
Repairability			■		■						■	

Figure 43. *Harris profile: IMU integration concepts*

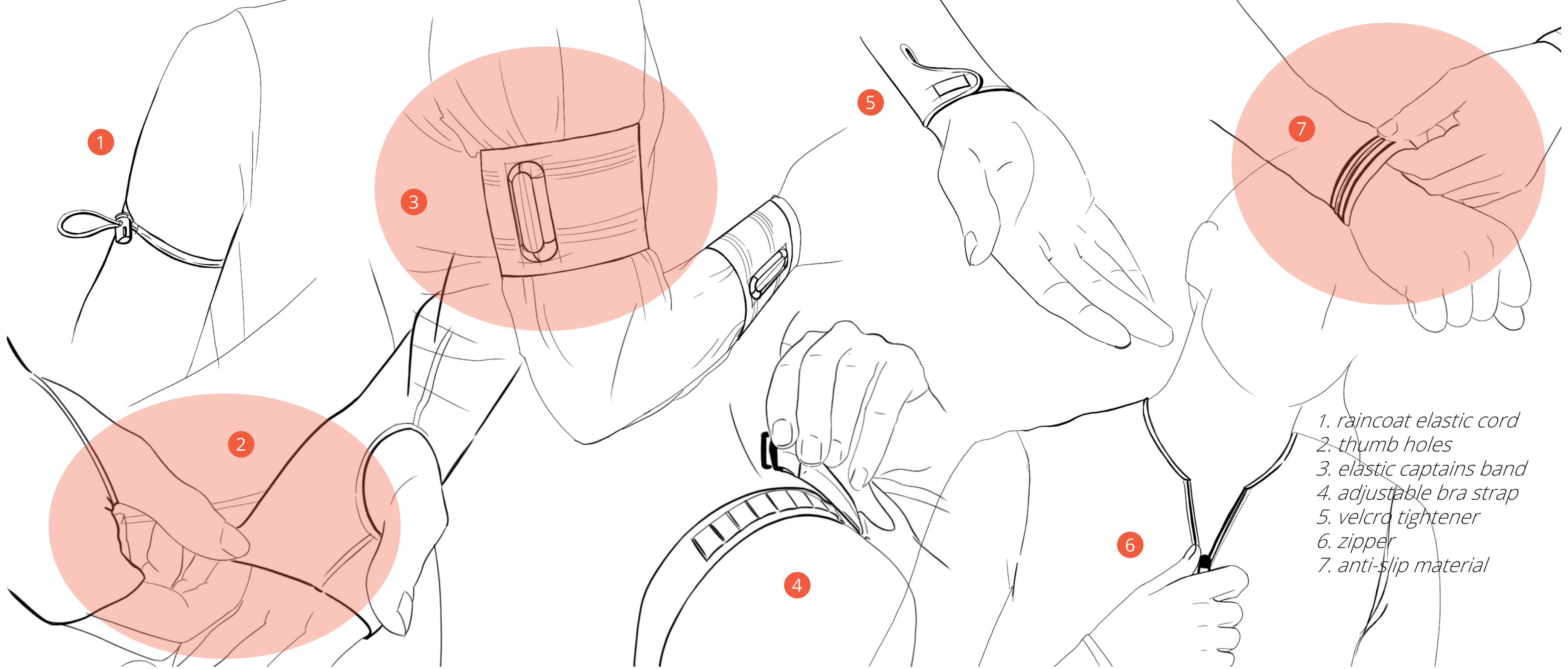


Figure 44. *Ideation: keeping sensors on their place*

8.3. IMU stability in smart shirt

A key design aspect is ensuring the IMUs are securely positioned on the body for accurate motion capture. Initial ideation concepts are shown in Figure 44.

The raincoat elastic (1), bra strap (4), and Velcro (5) ideas tighten the shirt at specific points but require adjustments after putting it on. This could be time-consuming and may compromise motion capture accuracy if not fitted properly.

Additionally, the raincoat elastic (1) can be uncomfortable due to pressure on the upper arm, and the bra strap (4) may be difficult for patients with dexterity issues.

The zipper (6), inspired by ice skating suits, provides a tight fit and is easy to pull on. However, it was dismissed because it requires two hands to zip, making it impractical for the one-handed use requirement.

Figure 46. *Smart shirt first textile prototype*

Figure 45. *Ideation: IMU stability*

PROTOTYPE SHIRT

The thumb hole (2), captain's band (3), and anti-slip elastic band (5) were further explored. The thumb hole is commonly used in tight sports shirts for women and helps keep the shirt in place during extreme movements. The captain's band fits tightly and presses the sensor against the skin, making it a promising option, though it may be less comfortable. The anti-slip elastic band could be a simple solution that tightens the fabric over the sensor, allowing the shirt to move smoothly with the skin, as the skin and elastic adhere to each other.

Prototypes
As a next step in the development of the smart shirt, prototype implementations of the proposed ideas were created using a "HEMA dames temptech t-shirt black" and prototyping fabrics available in the applied labs (see Figure 46).

THUMB HOLE

The thumb hole was designed to be very tight to ensure that the sleeve moves correctly with the hand's motion. However, it proved impractical for varying hand sizes. Additionally, while the sleeve aligns with the hand movement, the wrist area remains loose, causing the IMU to float since the wrist is narrower than the hand and the area closer to the elbow is larger.

ANTI-SLIP MATERIAL ON UPPER ARM

The elastic band on the upper arm effectively presses the sensor against the skin and maintains stability. However, it is challenging to pull on as it does not glide over the skin but sticks and the arm needs to go through the elastic band from the hand up to the upper arm. Additionally, the band is very tight and narrow, which causes it to knead into the softer tissue of the upper arm, creating discomfort (see Figure 45).

ANTI-SLIP MATERIAL ON WRIST

The elastic band on the wrist effectively presses the sensor against the skin. The discomfort due to tightness and the difficulties of pulling on are less problematic than with the upper arm. This is due to the wrist's bony structure and the fact that only the hand needs to go through the elastic band when pulling the shirt on.

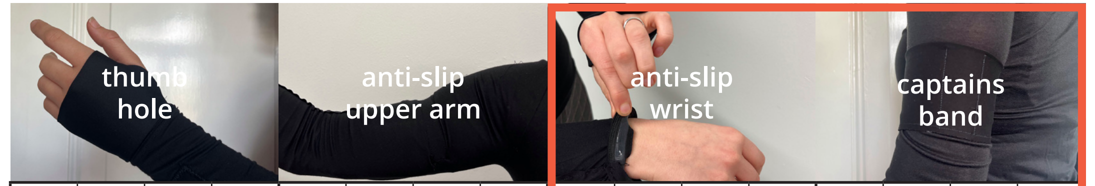
CAPTAINS BAND

A wide band of thicker elastic fabric folded double and sewn in a tighter manner than the shirt where the sensor is pushed on the arm. This makes the shirt only around the sensor tighter, the rest of the shirt is not compromised on comfort. After a while you do not feel the band anymore, because it is wide enough to divide its pressure over the upper arm.

IMU stability concept choice

The prototypes were evaluated using a Harris profile (see Figure 47). Different designs were chosen for the IMU at the wrist and the IMU at the upper arm to ensure optimal stability. An elastic band with anti-slip material was selected for the wrist, forcing the sensor to follow the lower arm's movements. Due to the wrist's bony structure, no excessive discomfort is expected caused by the very tight elastic band.

For the upper arm, the captain's band concept was refined. Instead of a literal captain's band, the shirt itself is sewn tighter around the IMU areas. Additionally, a thicker, more elastic sports shirt must be used as the base. This modified approach integrates seamlessly in the shirt, with tightness gradually increasing towards the sensor to avoid discomfort without adding material.

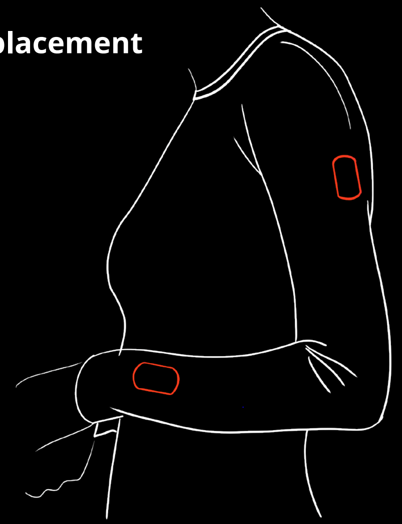


	thumb hole				anti-slip upper arm				anti-slip wrist				captains band			
	--	-	+	++	--	-	+	++	--	-	+	++	--	-	+	++
Sensor stability	■							■			■					■
Comfort			■		■					■						■
Ease of use				■	■						■					■
Fit		■			■					■				■		
Simplicity	■						■				■				■	

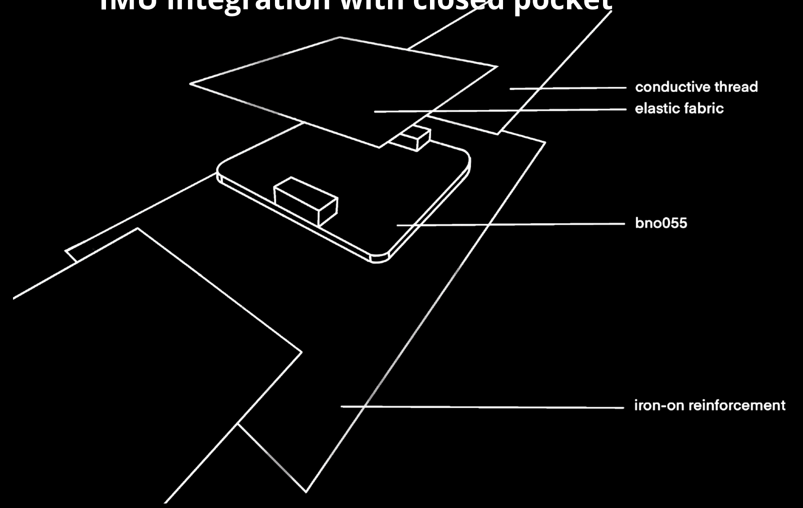
Figure 47. *Harris profile: IMU stability concepts*

Design concept: for integrating the IMUs

IMU placement



IMU integration with closed pocket



Anti-slip elastic at wrist
to secure stability of the lower arm IMU

Sewing the shirt tighter
to secure stability of the upper arm IMU

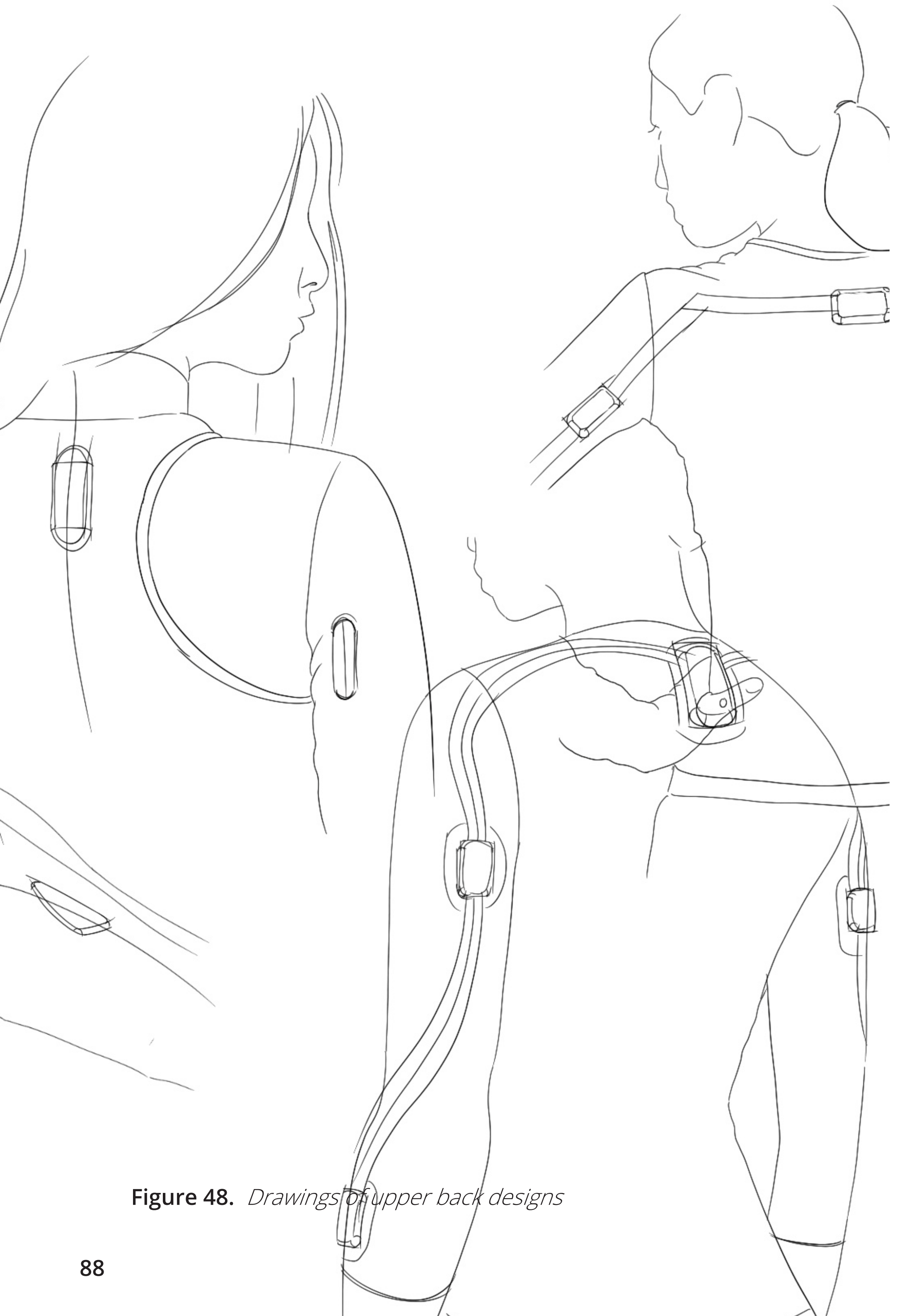


Figure 48. *Drawings of upper back designs*

9. Upper back design

The upper back presents a complex challenge in the shirt design. It involves integrating the final IMU, multiplexer, and microcontroller while accounting for the movement of the shoulder blades, neck, and spine. This chapter discusses the steps taken to address these challenges and presents the final upper back concept design.

9.1. Placement of electronics

First decide on were to place the IMU, the multiplexer, the microcontroller and the battery on the back. The first decisions that were made, to limit the options are:

Upper back placement. The IMU and electronics are placed on the upper back, close to the wires coming from the arms. This position is ideal for capturing shoulder rotations. Placing the components between the shoulder blades allows better alignment with the torso's movements.

Separation of components. The IMU and other electronics are kept separate to avoid a bulky unit. Keeping the IMU fixed to the skin is crucial for accurate motion capture. The microcontroller, which also includes an unused IMU, is placed separately to avoid interference and potentially contribute additional data later.

Discarded wider shape. A wider shape was rejected as it caused discomfort when moving the shoulder blades, detaching from the skin and hanging loosely.

Prototype
Based on these initial decisions, a small prototype was created with the IMU placed on top, as this is the flattest part of the upper back and appears to remain stable. The prototype was tested using 3D printed shapes (Figure 42), with Shape 1 being long, small, and thick, and Shape 2 being wider, following the shoulder blade lines and tapering at the bottom.

Insights
The testing showed no noticeable difference between the two shapes; both were barely felt during the tests. However, the shirt needed to be thicker and tighter to improve stability, as the test shirt was too thin. It was also observed that the shirt curled up at the back of the neck when the shoulder blades moved or the arms were raised, causing the IMU to come loose. Tightening the collar helped reduce this, but the upper back still experienced the most movement. The lower part of the spine showed less movement, indicating that placing the IMU under the main unit would enhance stability. This setup, common in literature, ensures the IMU remains stable on the skin and may allow for more useful microcontroller data.

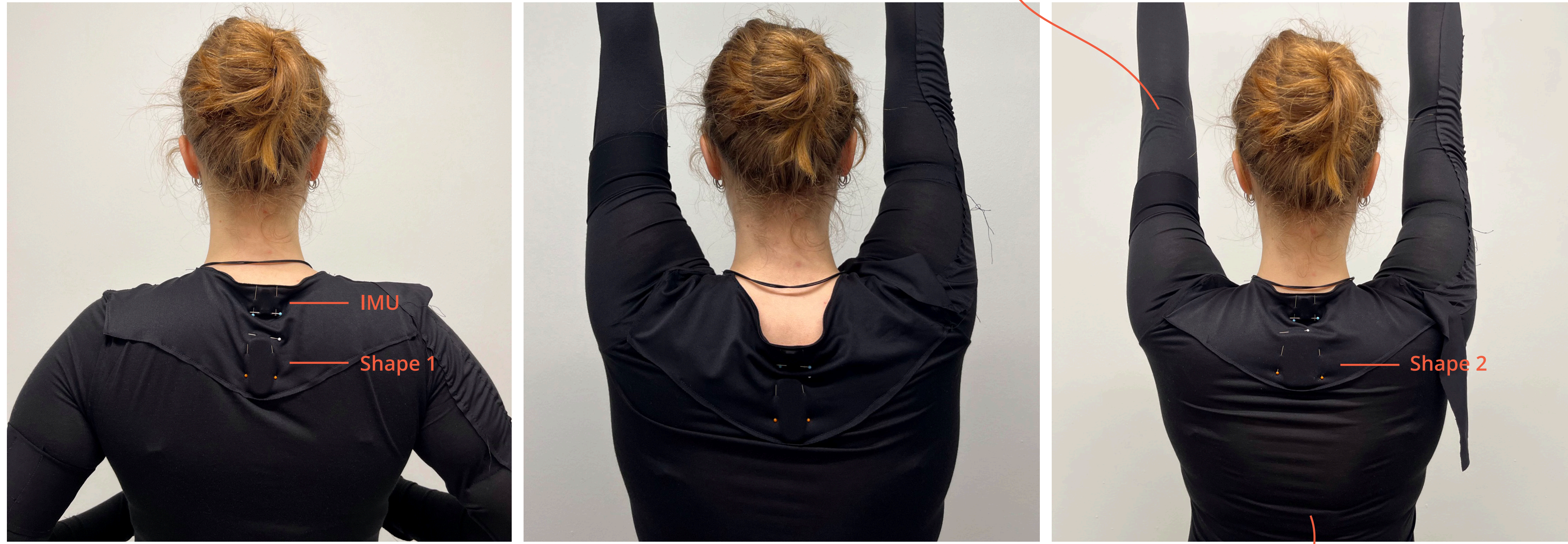


Figure 49. *Prototype of back configuration with IMU on top, tested in different poses*

9.2. Main node design

After deciding on the placement of the IMU and main node the next challenge is to design a main node that combines the multiplexer, microcontroller, and battery and effectively manages the connecting wires from the IMUs. Moreover, the comfort of the patient needs to be kept in mind.

Three concepts with different combinations of parts were thought of, each with its unique advantages and disadvantages.

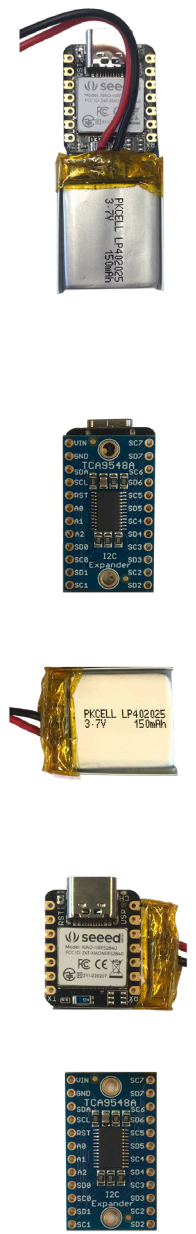


Figure 50. *Concepts of the main node design*

ONE PIECE

The multiplexer, battery, and microcontroller are integrated into a single unit with fixed connections, designed in a stacked and elongated form. This approach is more compact. The design is simple, because there is no need for additional components. Users also benefit from ease of use, as there is no need to connect any components themselves. However, power management becomes a challenge, requiring an on/off button. The integration of all components in a confined space increases wiring complexity, which complicates the making process.

SEPARATE BATTERY

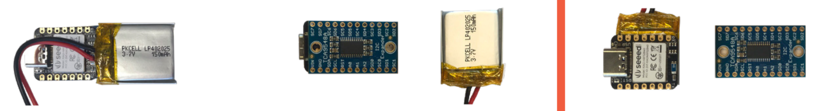
The second concept separates the battery from the multiplexer and microcontroller, allowing the battery to be connected via a connector and detached as needed. This configuration enhances the battery's flexibility, enabling it to be disconnected for charging, replacement, or in emergencies, thus improving maintenance ease, longevity, and safety. However, the use of an additional connector increases the overall size of the device and introduces a potential failure point, which could compromise the reliability of the connection and overall durability.

SEPARATE MULTIPLEXER

The microcontroller and battery are combined into one unit, while the multiplexer is kept separate. This design excels in ease of maintenance; both the microcontroller and battery can be easily removed from the shirt for charging, reprogramming, connecting to a computer, or repairs. By isolating the multiplexer, the wiring is simplified, improving manufacturability. The primary disadvantage of this concept is the increased size due to the additional connector required for the multiplexer.

Main node concept choice
To choose between the concepts the weighted criteria method from the Delft Design Guide (2021) was used. Figure 51 shows the resulting table.

The Separate Multiplexer emerged as the most suitable option, scoring highest due to its reliability and repairability. This concept also provides space for the complex wiring around the multiplexer. By separating the multiplexer instead of creating one large main node, the design becomes more flexible, allowing it to move with the wearer's back movements.



		One unit		Battery separate		Multiplexer separate	
Criteria	Weight	Score	Weighted score	Score	Weighted score	Score	Weighted score
Reliability	5	2	**10**	3	**15**	5	**25**
Compactness	4	5	**20**	3	**12**	3	**12**
Wiring simplicity	4	1	**4**	3	**12**	4	**16**
Ease of maintenance	3	2	**6**	4	**12**	5	**15**
Flexibility	2	3	**6**	4	**8**	4	**8**
Total			46		59		76

Figure 51. *Weighted criteria table of main node design*

Design concept: upper back design

IMU
The IMU is placed in the middle of the back for stability, minimal movement, and close contact with the skin, allowing the fabric to tighten around the torso if needed.

Multiplexer
The multiplexer is positioned between the shoulder blades. Wires from the arms come from the sides, IMU wires from the bottom, and wires to the microcontroller and battery from the top. This setup keeps the wiring organized.

Microcontroller
The microcontroller and battery are placed on top of the shirt, with the USB-C port still accessible.

Integration
The electronics integration follows the same approach as the IMUs, with elastic material covering the components for a secure and comfortable fit.

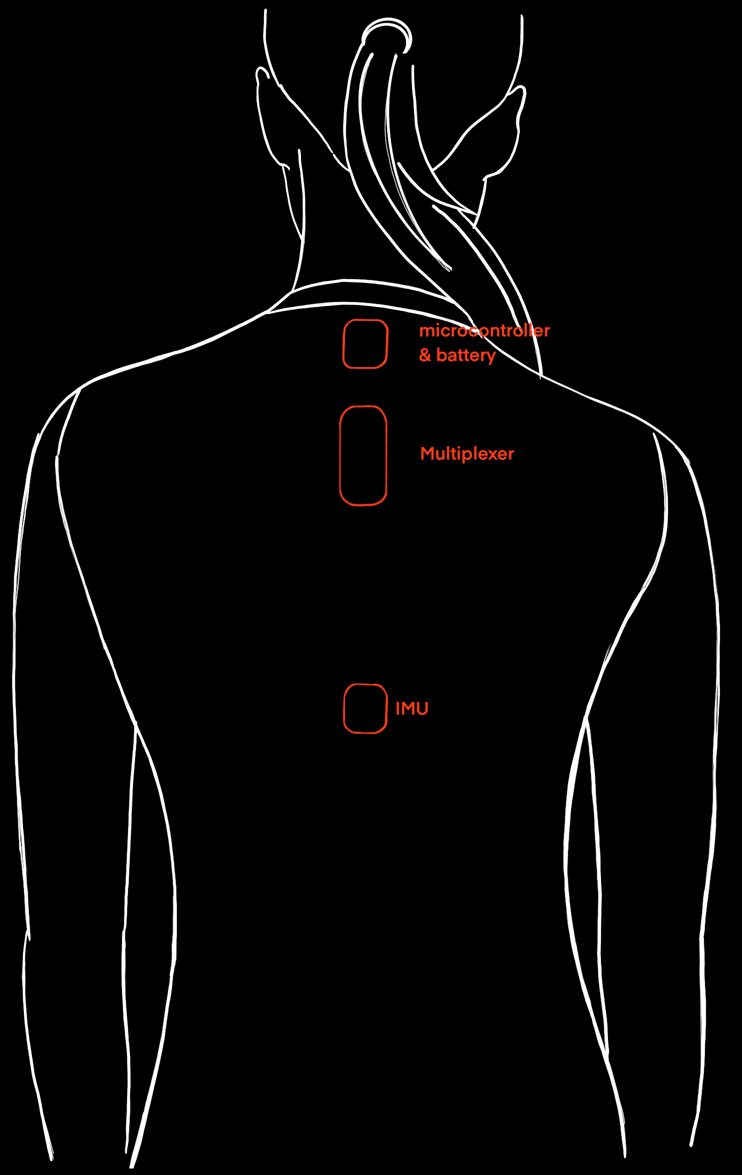


Figure 52. *Placement of electronics on the upper back of the smart shirt*

Figure 53. *Conductive thread integrated in a elastic band*

10. Wiring with conductive thread

Innovations in smart clothing technology often revolve around integrating electronics seamlessly into wearable fabrics. One way to do this is replacing the conventional wires with conductive thread which can directly be sewn in textile. This chapter delves into the use of conductive threads for connecting the sensors in the smart shirt. Material choices, placement strategies, integration in the shirt and the connection to the sensors are discussed. The chapter ends with a design proposal for the final prototype.

10.1. Conductive thread choice

To connect the electronics in the shirt, traditional copper wires covered with plastic have been replaced with conductive thread. The benefit of using conductive thread is that it integrates seamlessly into clothing and feels similar to regular sewing thread, making it easy to sew into garments, as done by Alamel et al.

However, a major drawback of directly sewing the thread into the shirt is its fragility, which affects the durability of smart garments. To solve this, a version of conductive thread integrated into an elastic band was chosen (see Figure 53). This allows the elastic band to stretch when the fabric moves, reducing strain on the conductive threads. This approach was inspired by similar applications in sensor tights developed by TU Delft and other smart suits (see Benchmark).

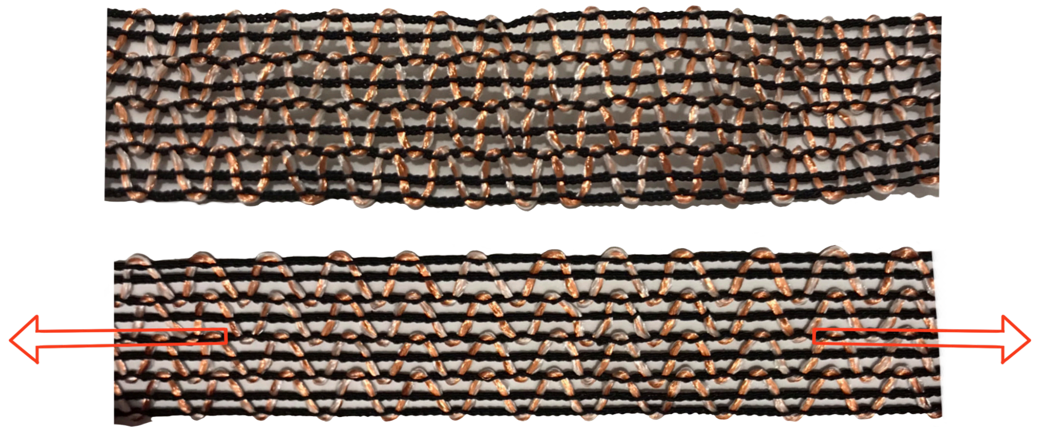


Figure 54. *Conductive thread integrated in elastic*

10.2. Placement of conductive thread

When determining the best way to connect and place the conductive wires, the following aspects were considered:

Straight path. The wires should connect the IMUs in a relatively short path, avoiding additional length of the wires which increases the total resistance and excessive material use.

Bends. As the elastic passes over the contours of the body, it needs to make bends and curves. Additional care should be taken to ensure that there is no excessive tension on the shirt, which could lead to skewing or misalignment.

Body movement. Wire placement must account for body movement, especially at the joints like the elbows and shoulders, where extreme bending occurs. The design should ensure that the elasticity can accommodate these movements without causing damage to the conductive threads or the fabric.

High impact points. The placement strategy should avoid areas prone to excessive wear or frequent impacts, which could degrade or break the threads.

Chosen placement strategy
The different placement strategies were explored by drawing different options and pinning these on a mannequin. For a visual representation of these ideas and the specific placement strategies on the body, see Appendix G.

Placement strategy in Figure 55 proved to be the most promising. The wires are placed over the front side of the arm, around the elbow, which bends less than the top or inside of the elbow. This positioning helps minimize stretching and folding of the wires. The path from the upper arm to the lower arm sensor follows a relatively straight line. The wires are positioned on the outside of the arm, making them more exposed to high-impact situations, such as bumping into objects. However, placing the wires on the inside of the arm would lead to faster wear due to increased friction with the body during movement. The decision to place them on the outside was made because the risk of damage is estimated to be lower when the user engages in exercises specifically designed for the smart shirt's intended use.

On the back, the conductive threads are routed along the top, around the most mobile part of the shoulder blades. This minimizes excessive movement and reduces the risk of excessive stretching of the elastic.

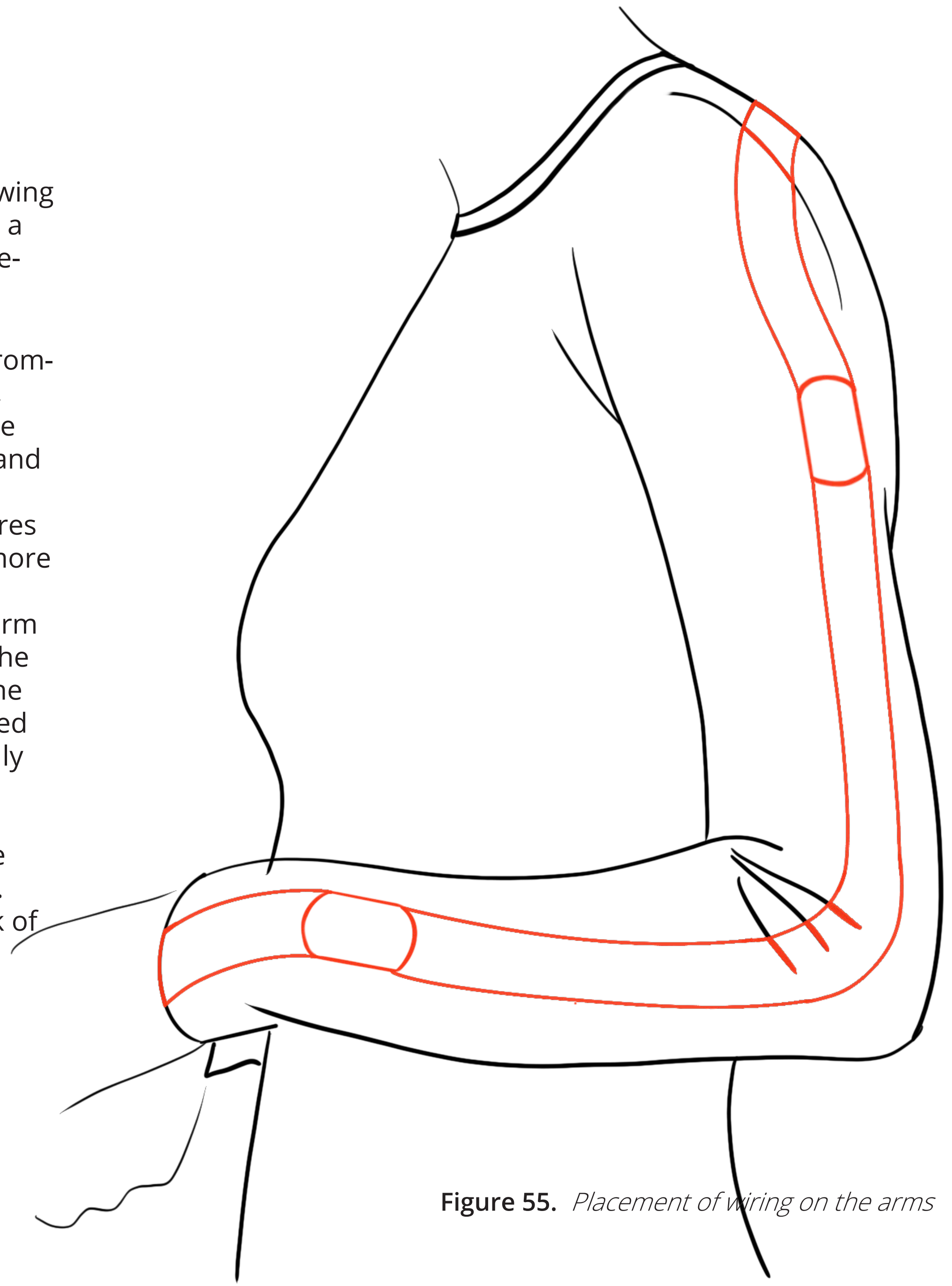


Figure 55. *Placement of wiring on the arms*

10.3. Integration of the conductive wire

Integrating the conductive wires into the shirt requires attention to two main points: attachment of the wires on the garment and secure connections between the wires the IMUs, and the multiplexer. These integrations must meet several key requirements, including wearer comfort, stable wire positioning, ease of separating electronics from textiles at the end of life, robustness, manufacturability, flexibility at bends, and ensuring that no strain is placed on the IMU connections.

Wire attachment
Several methods were tested for integrating the conductive wires into the shirt:

Zigzag stitch. A wide zigzag stitch securely fastens elastic over the conductive threads without damaging them. This provides stability and evenly distributes stretch. However, at the end of life, thread removal is difficult, as all stitches need to be undone.

Elastic tube. A fabric tube allows the elastic band with integrated conductive threads to pass through. This method protects the threads and allows easier removal.

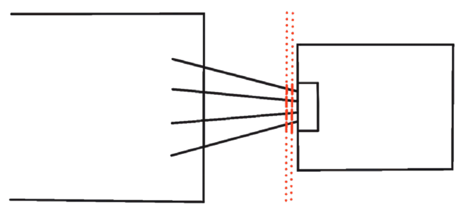
Multiple prototypes were tested (see Figure 56). A combined approach was chosen. Minimal zigzag stitching is applied only at high-stress bends, while the rest of the conductive elastic runs through a tube made from jersey bias tape. This pre-folded fabric handles curves smoothly without excessive creasing.

Figure 56. *Prototypes of wire attachment*

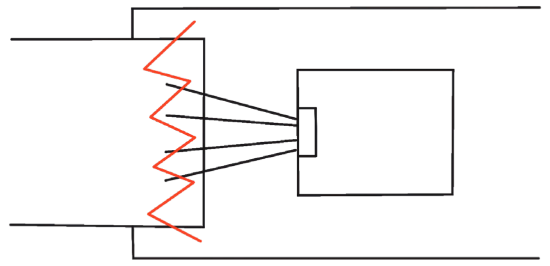
Connection to the IMUs
The conductive thread and conventional wires from the electronics will be connected using ferrules. A potential issue is that strain could be applied to the connection when the conductive thread is stretched. Figure 57 shows several ideas we that prevent strain on the IMU connections.

A combination of the non-stretch base layer and stop stitch was chosen for optimal strain relief and protection. The printed case and wire loop were avoided to reduce bulk and hard materials, ensuring better comfort with textile-based solutions. This approach also helps prevent pulling on the ferrule connection.

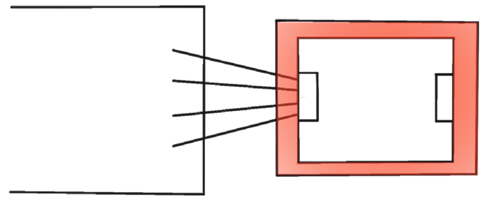
Figure 57. *Different ideas to prevent strain on IMU connections*



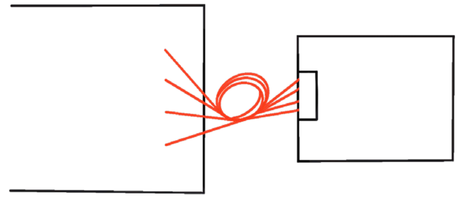
Stop stitch. A stitch placed to prevent pulling forces from reaching the connector.



Non-stretch base layer. The ends of the conductive elastic are sewn onto a piece of non-stretch fabric, so any pulling force is absorbed by the fabric instead of the IMU.



Printed case. A protective casing that prevents the connector from being pulled out of the IMU.



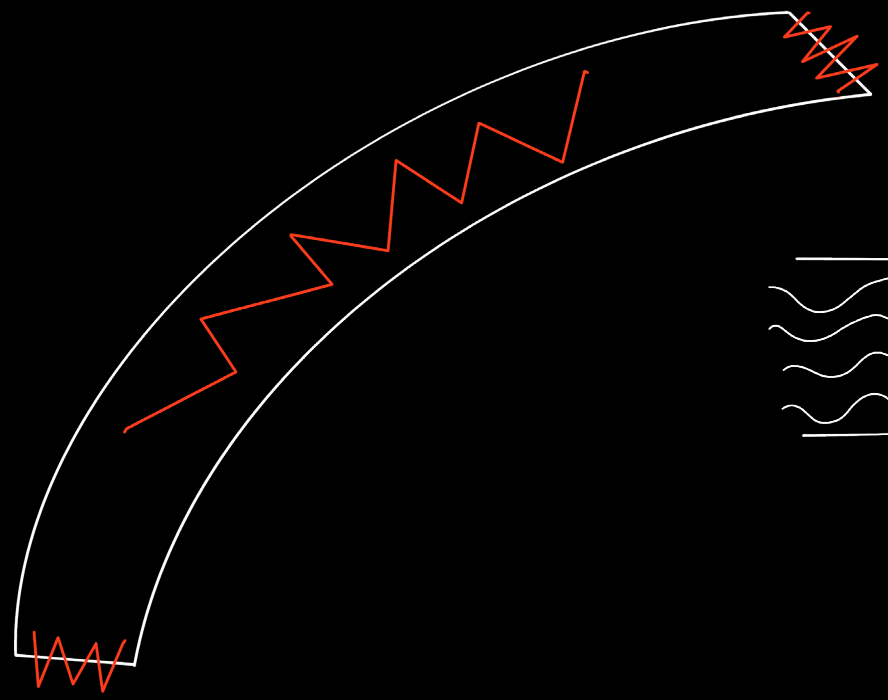
Wire loop. Extra length of wire is looped in, so that any pulling force is absorbed by the slack rather than reaching the IMU connection.

Design concept: wiring with conductive thread

The smart shirt design incorporates conductive thread integrated into an elastic band, replacing traditional rigid wiring to enhance comfort. This elastic band provides flexibility and stretch, with the wiring strategically placed on the arms to avoid high-impact areas.

Protective Tube
The conductive thread is secured and protected by a jersey bias tape tube, ensuring the thread stays in place. The zigzag stitch helps prevent shifting or movement of the thread.

IMU Connection
The conductive wire ends are connected to conventional wires linked to the IMUs and multiplexer using ferrules and shrink wrap for secure connections. Non-stretchable textile is used to fasten the conductive elastic wires, ensuring that when the textile stretches, the force is applied to the non-stretchable material rather than the IMU connections. This design reduces the risk of breakage or disconnection at the IMU connectors during use.



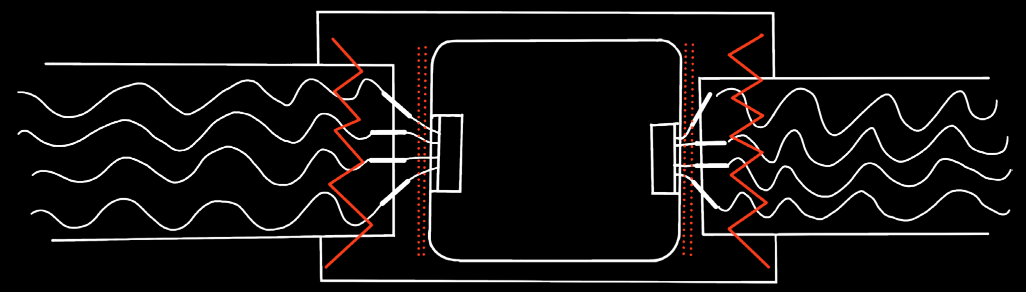


Figure 58. *Wiring integration concepts: wiring placing (left) and IMU connection(right)*

Figure 59. *Smart shirt product collage focused on aesthetic appeal*

11. Aesthetics

In addition to its functional design, the smart shirt also needs an appealing aesthetic, which is crucial for its overall success. This chapter outlines the steps taken and decisions made concerning the aesthetics of the smart shirt.

Aesthetics goals
Goals for the aesthetics of the shirt were set, which later on informed subsequent decisions. The aesthetic objectives for the smart shirt include:

Innovation visibility. The shirt should not appear as a typical garment but as a distinctly smart shirt.

Comfort and assurance. As a medical garment, it should exude comfort and assurance. Wearers should feel comfortable and appreciated, with a design that respects and enhances their body image.

Ability to move. The design should emphasize ability rather than disability, aligning with the rehabilitation goals of the user.

Functionality in wear. It should aid in correct and easy dressing, ensuring sensors are positioned accurately for optimal functionality.

Broad appeal. The design should be appealing to a diverse audience, reflecting the user group.

Product collage
As an initial exploratory step, a product collage was created (see Figure 59). This method, drawn from the Delft Design Guide, facilitates the translation of abstract aesthetic goals into tangible design elements. The collage was digitally composed using images from current sportswear and smart textile products. The selection of images was guided by keywords the keywords 'technology,' 'futuristic,' 'movement,' and 'effectiveness'.

The product collage provided the following insights:

Colour palette. The incorporation of neon colours (red, yellow, green, blue) along with silver, white, and gold details conveys a sense of futurism, innovation, and youth. These colours are strategically used to attract attention and denote the advanced nature of the shirt.

Background tones. The use of blue and black as background colours enhances the design's sleekness and timelessness, while also suggesting comfort and reliability.

Dynamic lines. The use of fast, dynamic lines gives a sense of movement, which aligns perfectly with the shirt's rehabilitation purpose. These lines also contribute to the perception of the shirt as a new and fast technology.

Emphasis on technology. Highlighting the electronics within the shirt, such as exposing golden or copper wires, clearly distinguishes it from ordinary garments. This design choice underscores the shirt's technological features.

Material effects. The use of shiny and shimmering materials adds an element of modernity and visual interest to the shirt.

Varied textures. Using different textures, the shirt visually segments into various sections. This division allows for clear identification of different functionalities and contributes to a distinct overall aesthetic that positively accentuates body shape.

Textile exploration
Building on the insights from the product collage, a secondary exploration involved putting the insights into practice in a textile prototype (see Figure 60). For this prototype basic materials and techniques were used available in the applied labs to recreate aspects observed in the collage. Trials included various stitches, thread types, colours, materials and sewing machine settings.

The insights gained from the textile prototype are summarised as follows:

Fabric gathering. Tight back-and-forth stitching on stretchable fabric tends to gather the material, affecting the garment's fit and aesthetics.

Colour visibility. Light blue, neon yellow, and white are highly visible against a black background. Denser stitches make these colours even more striking.

Ease & speed. Straight stitches are quicker and easier to sew, which is crucial for scalability and sleekness.
Reflective materials. While reflective materials (2) are highly visible and eye-catching, they pose challenges in sewing curves due to their rigidity.

Stitch layering. Placing multiple rows of stitches next to each other adds body to the section and makes it more prominent, enhancing both the texture and visibility of the design elements.

Figure 60. *Textile exploration of aesthetics*

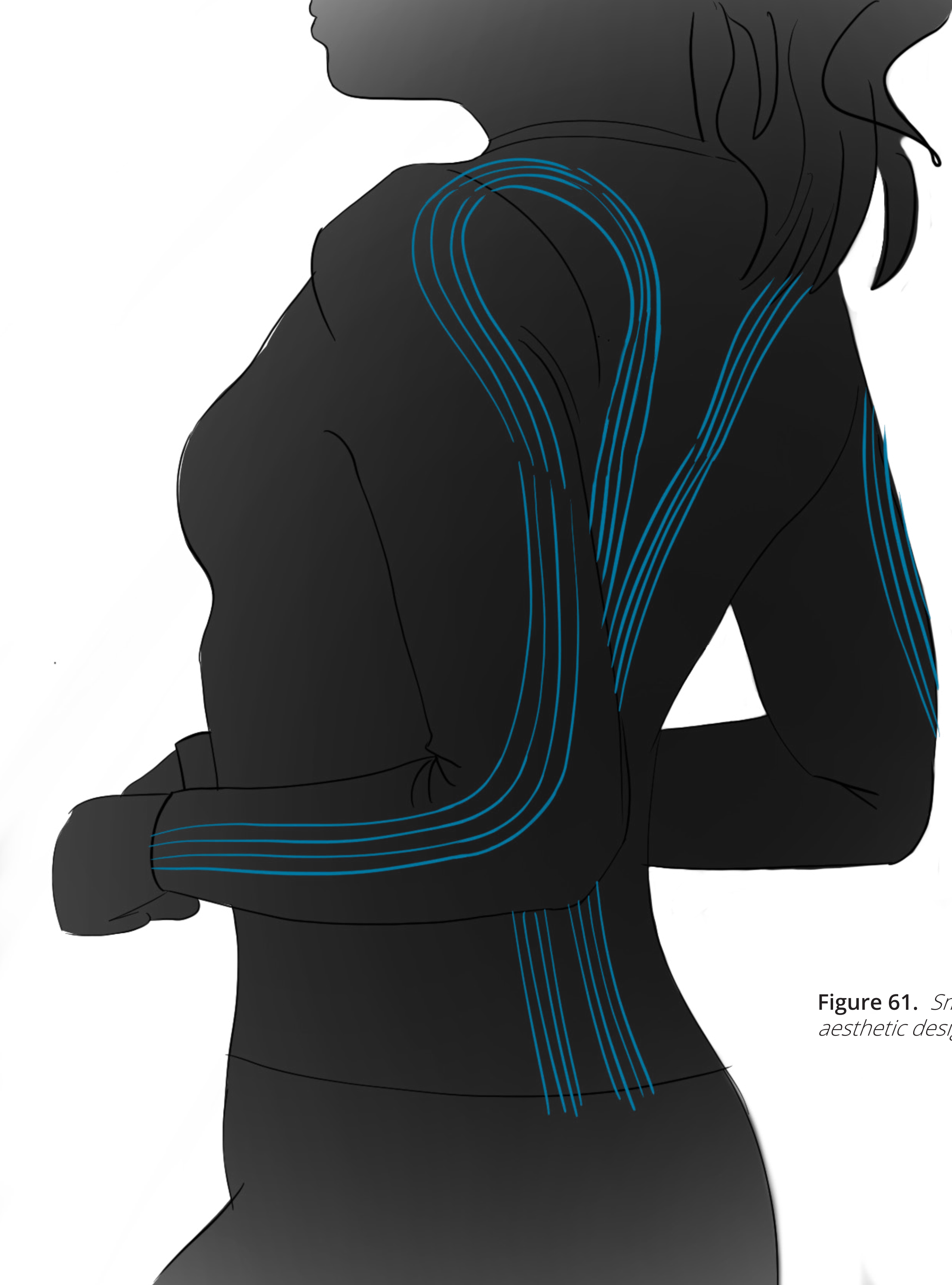


Figure 61. *Smart shirt aesthetic design*

Design concept: Aesthetics

In developing the final aesthetics of the smart shirt, several key decisions were taken by reflecting on the aesthetic goals: Innovation visibility, comfort and assurance, ability to move, functionality in wear and broad appeal.

Colour Selection
The shirt is primarily coloured black for several reasons. Firstly, a black shirt with the functional criteria required are readily available. Additionally, black is chosen for its sleek appearance, timelessness, and the universal appeal it provides. It also conveys a sense of comfort and reliability. Another advantage of using black is its ability to mask any inconsistencies in stitching, allowing the shirt to maintain a neat appearance.

Integration of Dynamic Lines
The design incorporates dynamic lines that follow the paths of the conductive threads embedded within the shirt. These lines not only highlight the technological features but also visually represent the functionality related to movement. This design element serves as a guide for users, indicating how to properly wear the shirt as the lines are aligned with the arms and back.

Visual and Functional Details
The dynamic lines are stitched with neon blue thread, using stitch type four as shown in Figure 61, was selected for its speed and neatness. The light blue colour stands out against the black fabric without overwhelming the design, providing just enough contrast to draw attention to the details.
Enhancement of Body Forms and Movement
The lines on the back of the shirt converge and extend downward and on the arms continuing over the wrists to the ends. This is done intentionally to emphasize the body's contours and the extent of movements.

Branding
The TU Delft logo is placed on the chest of the shirt, showing the were the shirt is developed.

Phase D

Deliver

In the Deliver phase the concepts from the develop phase are combined in one final prototype. The final design is presented here, and evaluated with a performance and user test. It will end with a conclusion of the project as a whole and some recommendations for future studies and designs are suggested. Finally, a personal reflection on the graduation projects is given.

This phase entails the following chapters:

Figure 62. *Movi: the final prototype*

12. Presenting Movi

This chapter presents Movi, the final smart shirt prototype designed to support rehabilitation through motion capture and visualisation. It covers the physical design, technology integration, user interaction, potential applications and the implementation of the shirt.

Figure 63. *Movi in action: user wearing the shirt and the visualisation on a screen*

The design concept
Movi is a smart shirt designed to make rehabilitation at home easier, more engaging, and more effective. Using IMU-based motion capture technology, it tracks the patient's movements and visualises them in real time. This gives patients instant feedback, helping them perform their exercises correctly and stay motivated throughout their recovery journey.

The shirt has a calm, comfortable appearance that makes it inviting to wear every day for a wide range of users. At the same time, bright, light blue lines flow smoothly across the arms in gentle waves, symbolizing the fluid, natural movements that patients are working toward in their rehabilitation. These lines make the invisible technology visible, reminding the wearer that this is not just an ordinary shirt, but a powerful tool designed to support their recovery.

Movi consists of a physical shirt with integrated electronics and a on-screen visualisation (see Figure 63). All the electronic elements in the smart shirt are represented in Figure 64.

Figure 64. *Overview shirt parts.*

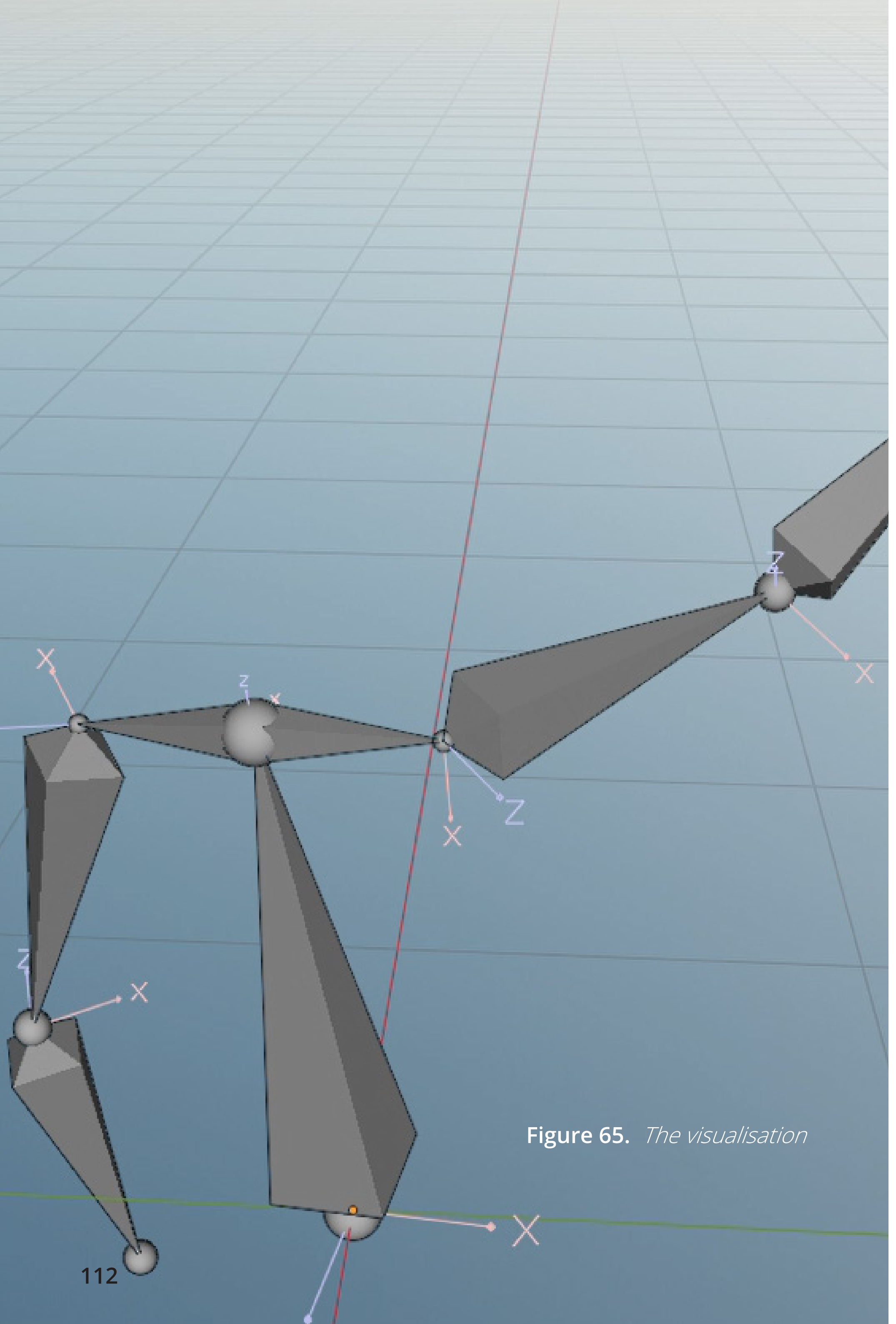


Figure 65. *The visualisation*

Real-time visualisation

The user's movements are captured by the BNO055s, which provide rotational data, quaternions, relative to a fixed world coordinate system. Thanks to on-board sensor fusion, the BNO055 outputs stable rotation data directly, simplifying the processing.

This data is collected via an Arduino IDE script (Appendix M) at 10 Hz, using the external crystal settings and streamed to the serial monitor. While Bluetooth is planned for future versions, the current prototype uses a USB-C connection for reliable data transfer.

In Blender, a Python script (Appendix L) reads the data from the serial monitor and processes it for visualisation. Although the IMUs maintain a global reference, their axes do not align perfectly with Blender's bones. To correct this, a fixed rotation offset is applied, based on a perfect T-pose, ensuring alignment without pose calibration.

The adjusted data drives the corresponding bones in Blender's armature, visualising movements at 24 frames per second, Blender's standard frame rate for smooth playback. Blender's flexibility allows easy customisation of the visualization, including rigging avatars to the armature for a more engaging, personalised feedback experience.

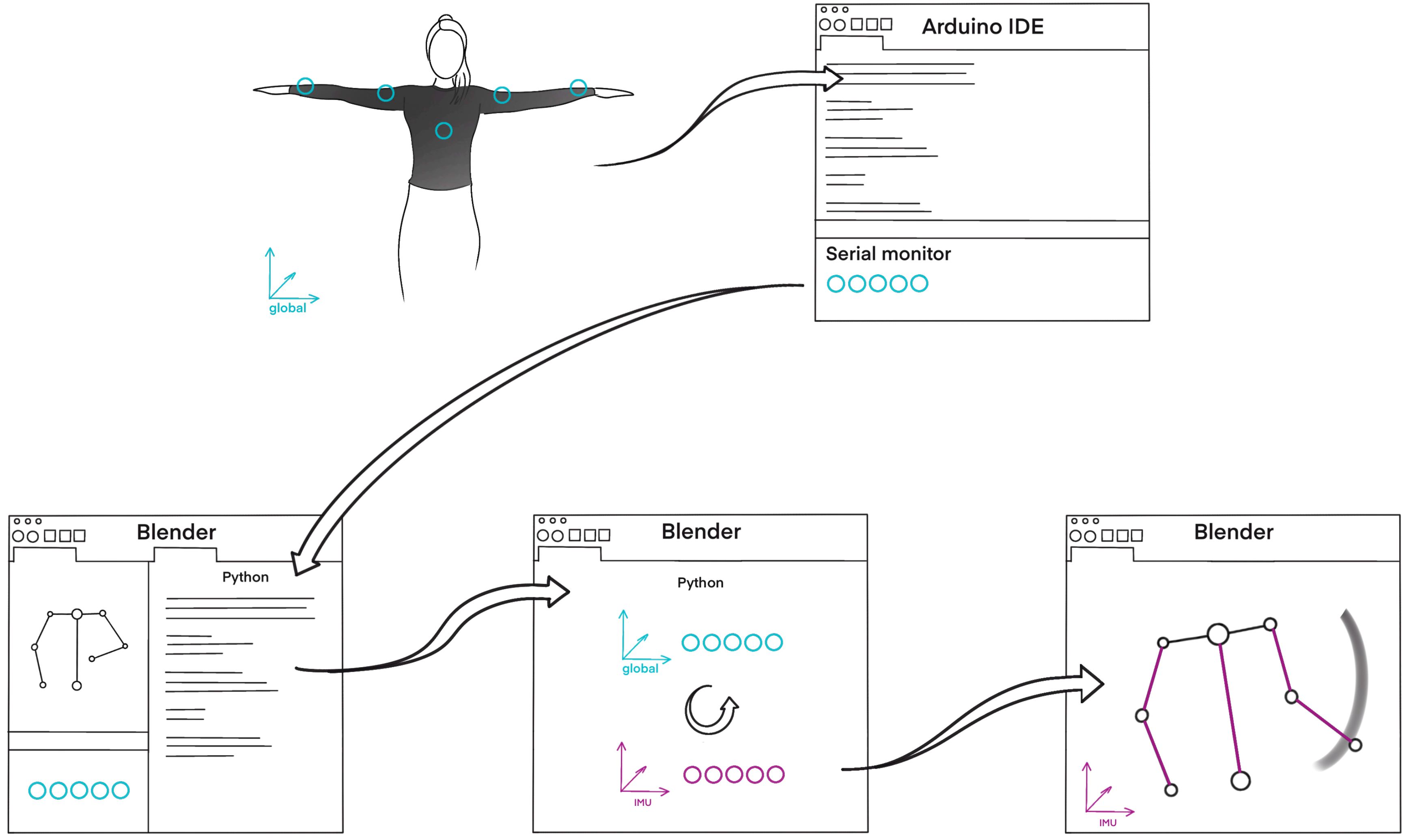


Figure 66. *Data flow diagram of rotational data: from IMUs to visualisation*

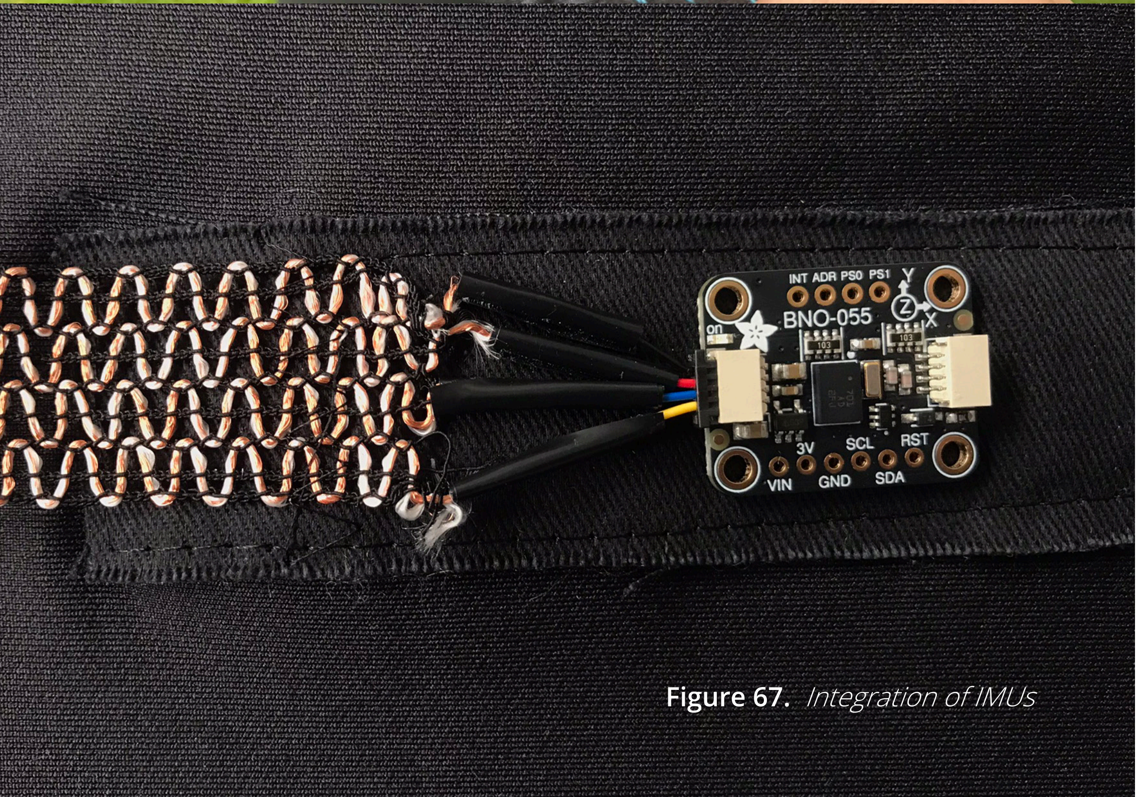


Figure 67. *Integration of IMUs*

Design details and materialisation

Base shirt
Movi is built from a pre-made sports shirt (Women Thermo LS IM-BLACK XS, The Indian Maharadja), chosen for its stretch, snug fit, and durable material. To ensure the IMUs sit firmly against the body, the shirt was taken in by 2 cm at the lower arms and torso where the back IMU is located. Anti-slip elastic is added inside the wristbands to keep the sleeves aligned with the wrist during movement.

Electronic components integration
To support the IMUs, multiplexer, and microcontroller, iron-on reinforcement and non-stretch sheet 100% sheet cotton fabric are sewn into the shirt at the IMU and main node locations. These form a stable base. Thick elastic bands are sewn over the electronics to hold them in place, protect them from movement, and reduce how much they can be felt or seen from the outside (see Figure 68).

Figure 68. *Overview of electronics integration*

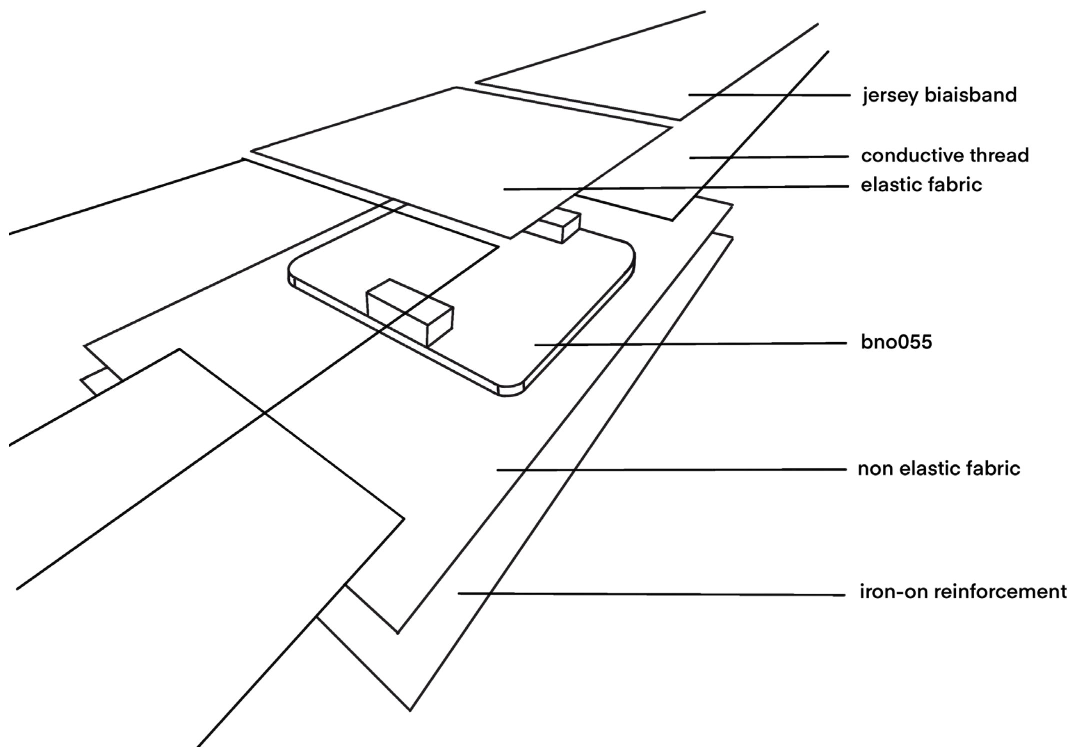
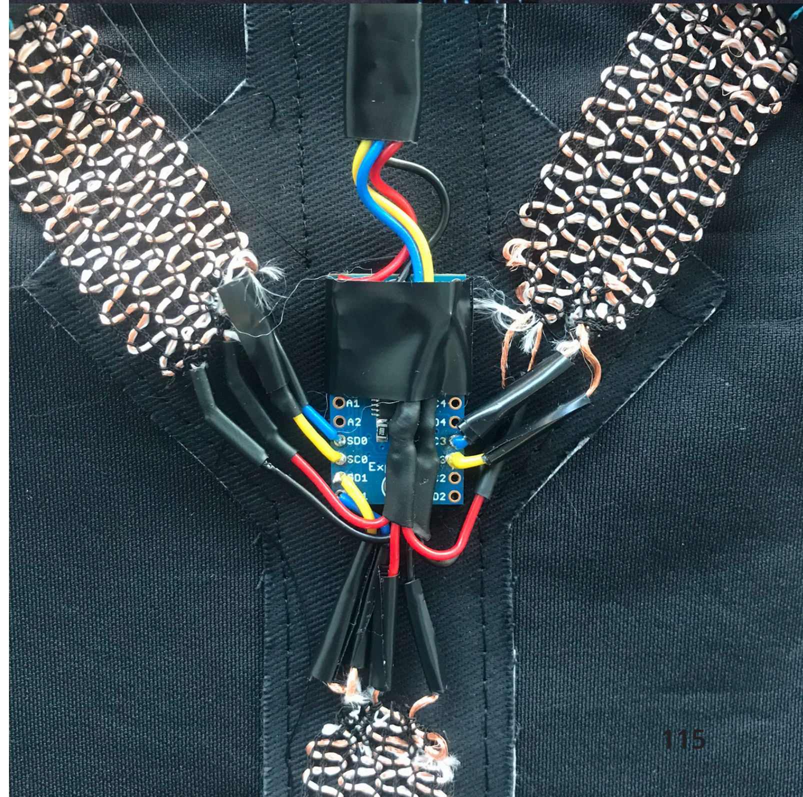


Figure 69. *Integration of main node on the back*



Wiring integration
Figure 70 shows the final wiring of the electronics set up with in the shirt. The conductive thread embedded in an elastic band is sewn along the shoulder curve for flexibility and durability. Its ends are fixed into the non-stretch zones to reduce stress on the connections. The wires that connect the electronics to the conductive thread are made from multi core wires. Ferrules are used to attach the sensor wires to the thread, insulated with heat shrink or electrical tape. These connections are then covered with jersey biais tape decorated with blue stitching, which also visually highlights the technology. The ends are anchored under the elastic bands that cover the electronics.

Sewing techniques
A combination of stitches is used within the shirt, because of their different strengths. A zigzag stitch is used to secures the conductive thread while allowing stretch. The shirt is reassembled with a straight stretch stitch, because of its room for stretch while not being wide. Non-stretch material is sewn on with a normal straight stitch. All of the named stitches are sewn with black mousse yarn, 100% polyester, because this is very thin and strong. Lastly, a decorative stitch with thick yarn (100 m/g) is used on the biais tape to highlight the integrated technology.

Assembly process
The electronics were mostly soldered before integration. The shirt was partially disassembled at the sides and inside the arms, materials and electronics inserted, and then resewn using a stretch needle. Most sewing was done with a conventional machine, but delicate areas, such as around wires or ferrules, were sewn by hand for precision.

Implementation
Movi is designed as an affordable and scalable rehabilitation tool with the potential to evolve into a broader health monitoring system. The estimated material costs of Movi are €220 (see Appendix J). The BNO055s contribute 65 percent to this price. These IMUs could be bought in bulk in the production stage to push the price down. With the lower price and available in multiple sizes, it is intended for individual purchase by patients, offering long-term value by supporting a faster and more independent recovery at home. Movi could also continue to be useful for injury prevention after the rehabilitation period.

Starting as a smart shirt for motion capture and visualisation, Movi can expand through integration with other wearables to enable full-body tracking and additional health insights. This could develop into a complete system with both hardware and software. The branding emphasises empowerment, independence, and engagement, positioning Movi as a personal recovery companion that makes rehabilitation approachable and motivating through simple, comfortable technology.

Movi is also built with end-of-life sustainability in mind. The electronics can be removed through pockets for reuse or recycling. The conductive wires are easily separable via minimal stitching, allowing the textile and electronics to follow separate recycling streams. Repairs can be performed by opening and resealing the seams, extending the product's lifespan.

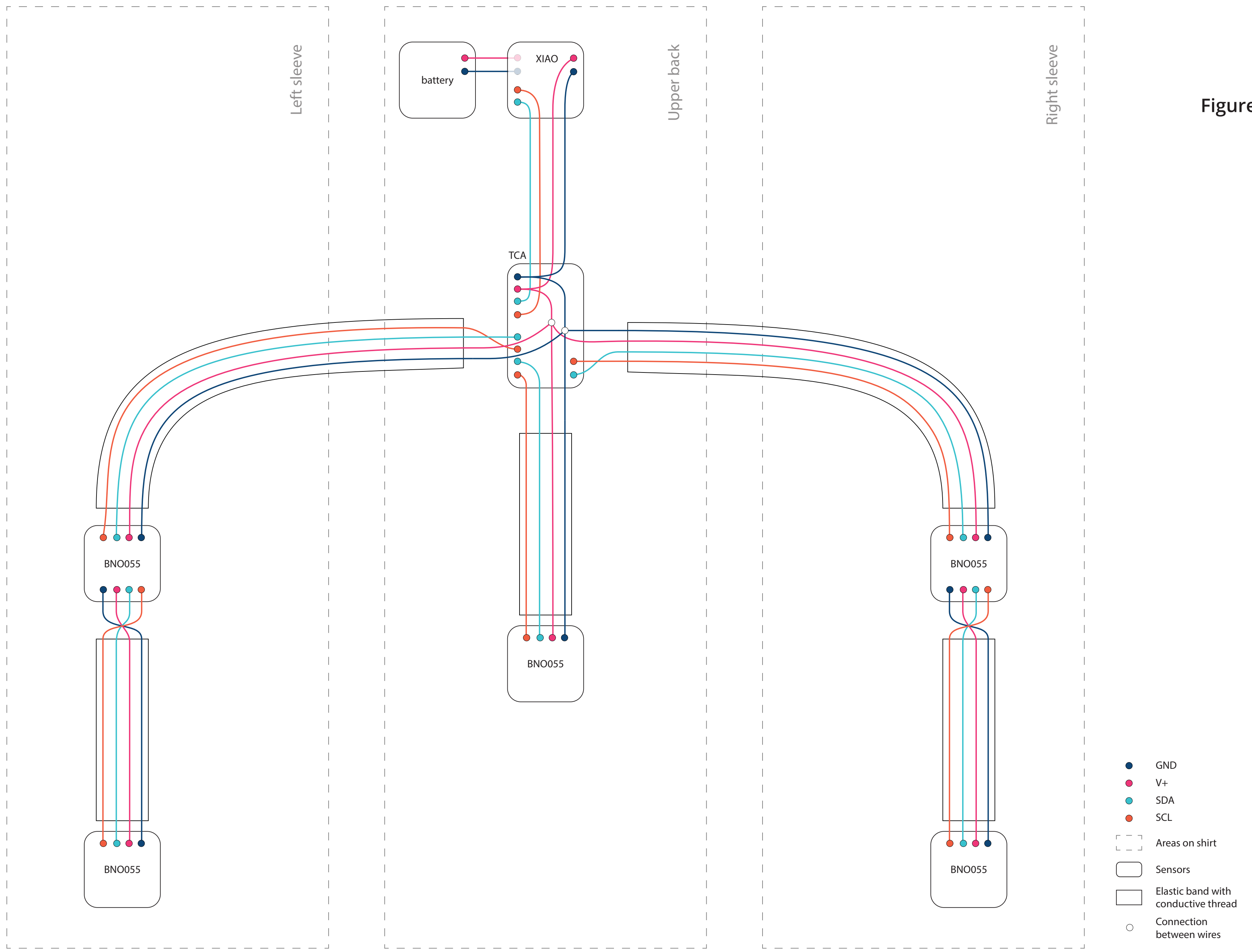


Figure 70. *Wiring of Movi*

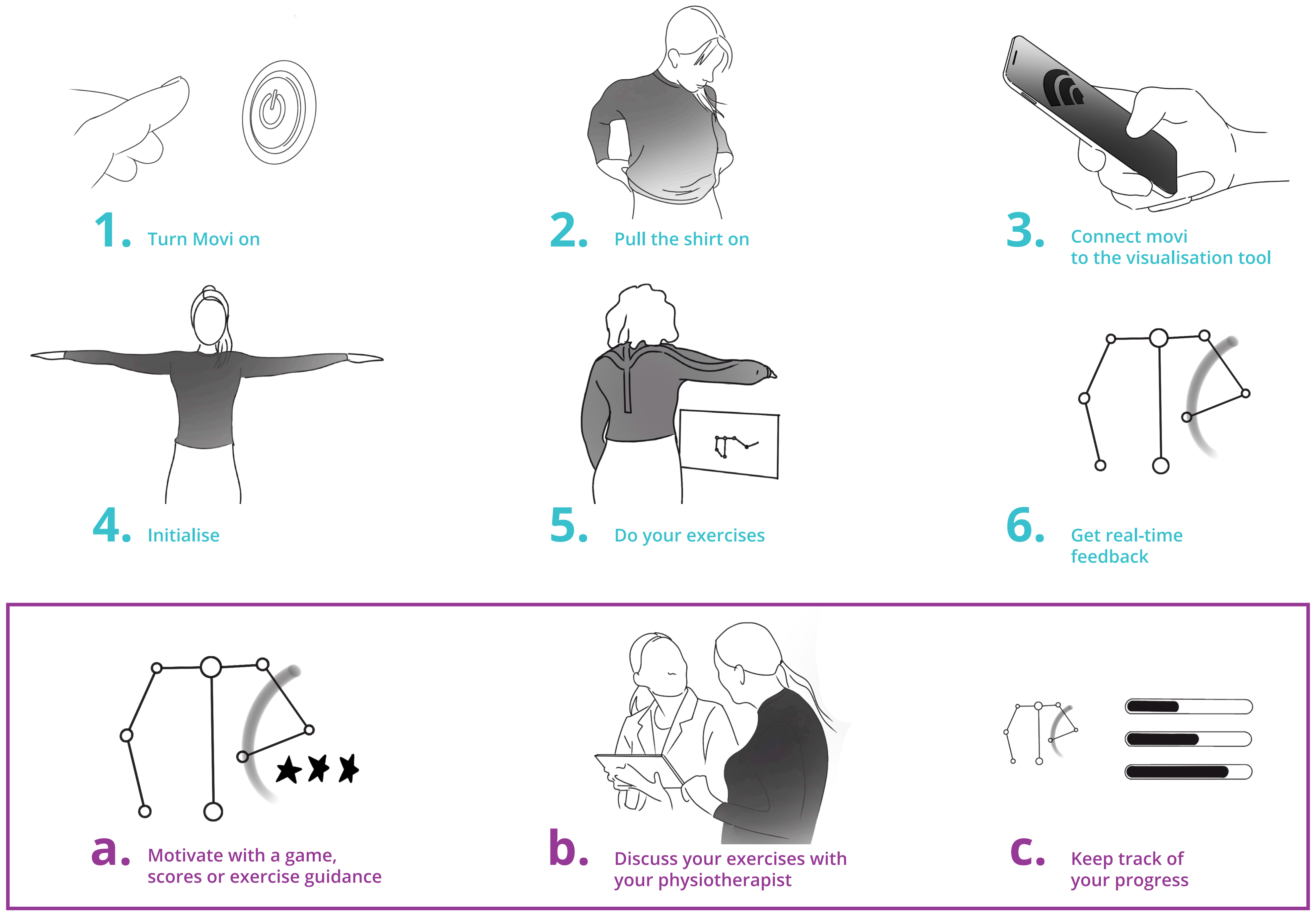


Figure 71. *Envisioned user interaction with Movi*

Interaction
Movi is designed for independent use, allowing patients to manage their rehabilitation exercises without the need for expert assistance. This sets it apart from many motion capture systems currently available, which often require complex setup and supervision.

The shirt is quick and easy to put on, thanks to its stretchy, form-fitting fabric, similar to that of a sports shirt. Its simple, seamless design was developed with accessibility in mind, particularly for users who may have limited mobility or can only use one arm. There are no straps, zippers, or buttons to adjust, allowing the user to put on the shirt independently and comfortably without the need for precise motions.

Once the shirt is on, it connects to a computer via USB-C, allowing the motion capture data to be transferred reliably to the visualisation software. After connecting, the system is initialised by having the user gently rotate their arms and back, allowing the sensors to stabilise and synchronise with Blender.

Following this brief setup, the user can begin their exercises while receiving real-time feedback on the screen. The motion capture data is visualised live, helping the user monitor and adjust their movements throughout the session.

Future applications
Movi's motion capture and visualisation system forms a strong base for a variety of applications.

In rehabilitation, Movi's visualisation could be expanded with tools that offer real-time feedback and guidance during exercises, helping patients perform movements correctly and confidently at home. This feedback loop supports better recovery outcomes and reduces the need for frequent clinic visits. Additionally, gamification, with scores, challenges, and progress tracking, can motivate patients, especially those in long-term therapy or hesitant to acknowledge their injury.

Movi also enables visual data collection from at-home sessions, giving physiotherapists valuable insights into patient progress. These videos can be reviewed during appointments, leading to more informed discussions and personalised adjustments to therapy plans.

Beyond rehabilitation, Movi can extend into sports performance and occupational health, providing motion insights to improve technique, enhance safety, and prevent injuries in both athletic and physically demanding work environments.

13. Evaluation

In this chapter, the Movi prototype is evaluated. The motion visualisation is tested for performance, fit, comfort, and user experience. Additionally, feedback from experts is gathered. The chapter concludes with the key findings.

13.1. Evaluation of movement visualisation performance

This section describes the evaluation of the performance of the movement visualisation generated by the shirt. The requirement for motion capture accuracy was:
To visualise mirrored movements so precisely that an expert observer could not distinguish any difference by eye.

Methodology
The system's performance was tested using a variety of static poses and dynamic movements, comparing the on-screen visualisation to the user's actual actions. Tests included neutral static poses as well as dynamic movements performed at different speeds. A screen recording was captured, and screenshots were taken from this recording to compare the poses visually. Additionally, the system was tested for drift by laying the shirt flat and collecting data every minute over a 10-minute period. Finally, the reaction time of the visualisation, defined as the delay between the user's actual movements and the visualised avatar, was assessed through simultaneous video recordings of both the user and the on-screen avatar.

Results
The detailed results of these tests are in Appendix I, K The key findings are summarised here:

Pose Accuracy. The T-pose, used as the base position for the simulation, showed minor differences between the user's pose and the visualisation (see Figure 72). Specifically, an upper arm deviation of approximately 5 degrees around both the x- and y-axes was observed. Additionally, the spine exhibited a misalignment of 18 degrees in sagittal tilt (x-axis) and 6 degrees in lateral tilt (y-axis). These inaccuracies

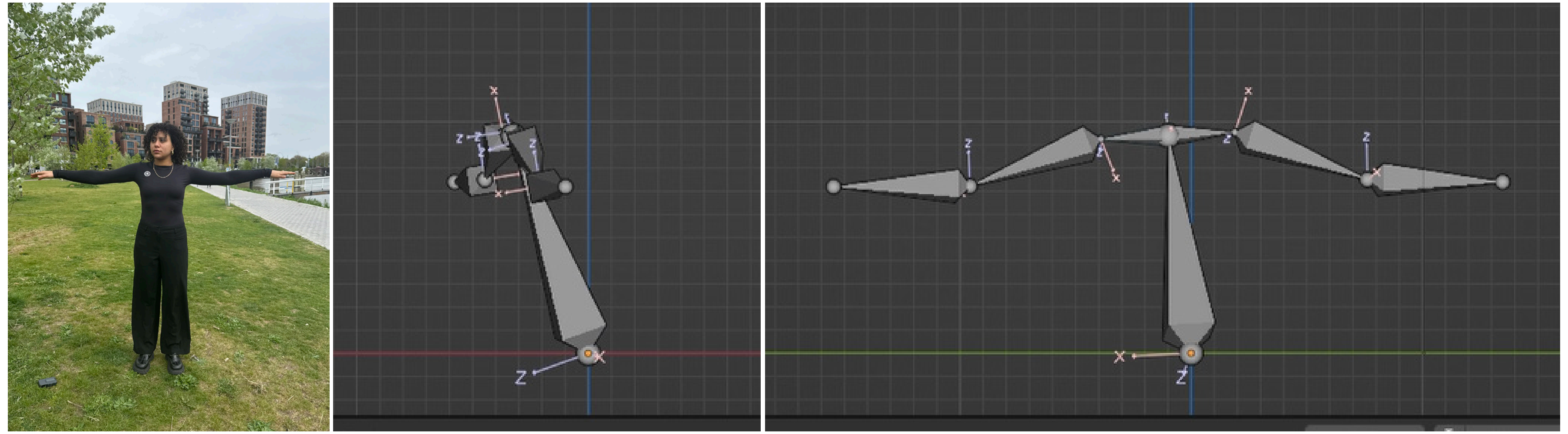


Figure 72. *User holding a T-pose and the associated visualisation*

appear to stem from differences between the initial positioning of the IMUs on the body and the corresponding base points of the IMUs in the software. This results in a systematic offset in the system's interpretation of the user's pose, affecting all subsequent poses.

Stable visualisation. No lag, distortion, or loss of tracking was observed during testing with various dynamic movements. Moreover, during the user test and the creation of the showcase video, no such issues were detected. Furthermore, no drift was observed over a 10-minute test period (see Appendix I).

Small visualisation delay. The reaction time analysis revealed an average delay of 0.233 seconds, indicating slight latency. This delay was also visible to the user (see Figure 73).

Initialisation period IMUs. It was observed that at the start of the visualisation, the avatar's movements did not immediately match the user's. This difference resolves after the user moves around with all sensors active, taking less than ten seconds. This indicates that the IMUs require a brief initialisation period.

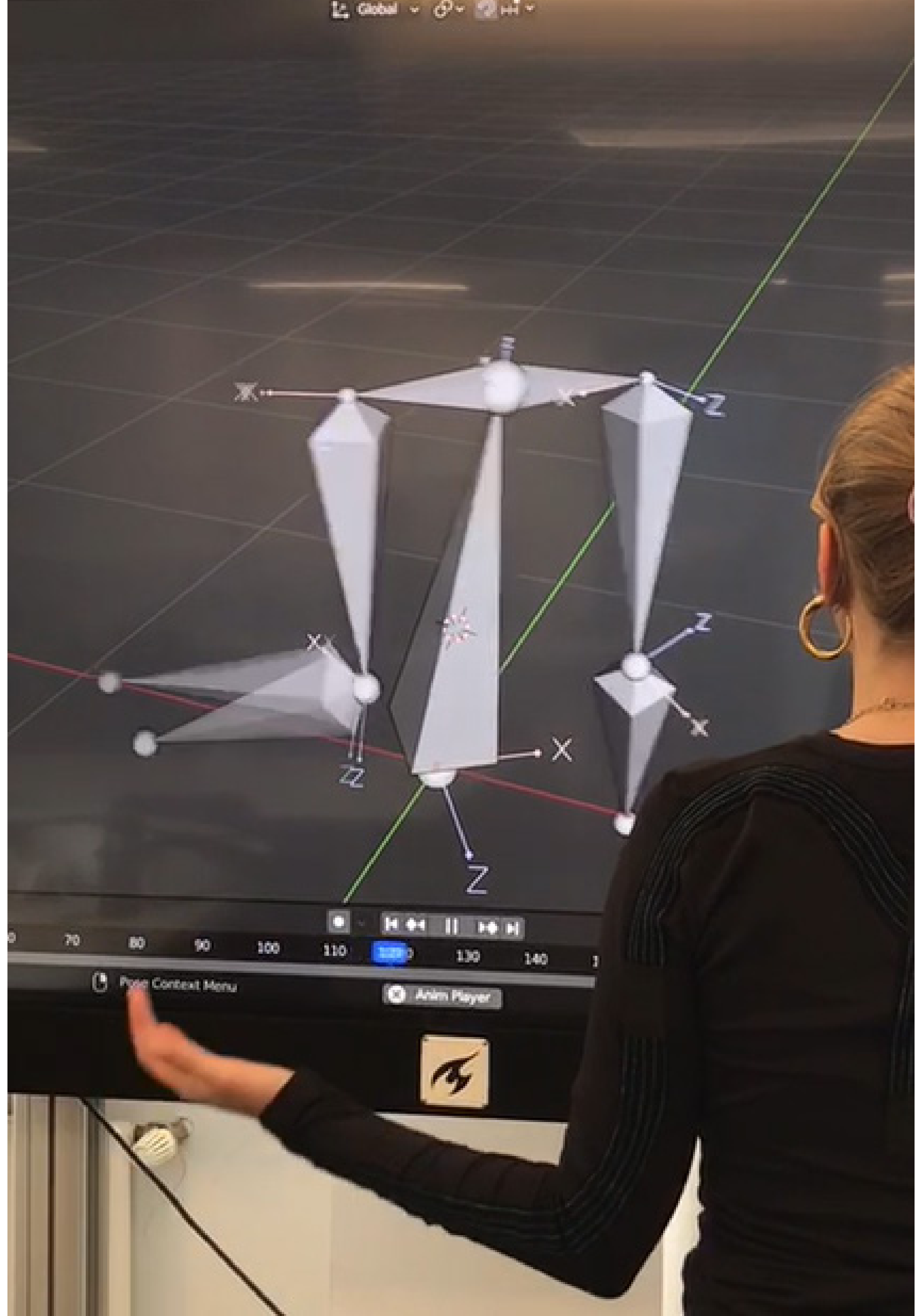


Figure 73. *Delay between shirt and visualisation*

Discussion

Overall, the visualisation accurately depicts the user's movements in real time and remains stable during prolonged use. Using Movi for an exercise session of 30-minutes, one of the requirements, is feasible and would provide insights into the movements of the patient.

However, there is a noticeable offset between the user's actual pose and the visualisation. Because this is seen already in the base pose (T-pose) this is likely be caused by an incorrectly appointed starting points of the IMUs. For therapeutic applications, such as gamified rehabilitation exercises, this level of inaccuracy is generally acceptable and does not hinder the user experience. However, for future diagnostic purposes, where precise motion capture is needed to assess progress or inform treatment decisions, this offset could affect the reliability of the system for rehabilitation specialist. Introducing a more elaborate calibration step could significantly improve accuracy, though implementing a user-friendly calibration process for patients remains challenging. While the starting position of the IMUs will be different for each patient because of different body types, using the average starting positions as starting position of the visualisation would already improve it.

The visualisation delay could be attributed to several factors, including: sensor response time, data transmission delay, processing time, and/or rendering time. The delay is also noticeable to users and may impact the effectiveness of real-time feedback. This latency can influence both the user's experience and their perceived trust in the visualisation, potentially influencing the willingness of both patients and rehabilitation specialists to use the shirt. Several strategies could be implemented to reduce the delay: increasing the sensor measurement frequency to lower response time, optimising the software to reduce processing time, and improving rendering speeds through data averaging techniques. Additionally, using a more powerful computer could help decrease overall latency. The IMU's sample frequency was initially set to 10 Hz for system setup, which is quite low. It was increased to the recommended maximum of 100 Hz for external crystal settings, effectively solving the latency issue. Since Blender's visualisation runs at 24 frames per second, implementing data averaging methods could further improve performance. While the current setup uses a USB-C connection, switching to Bluetooth would likely introduce further delay, so this should be considered in future designs.

The required initialisation period for the IMUs should be integrated clearly into the user interaction flow. A prompt within the visualisation software could instruct users to move briefly with all sensors active to complete initialisation, this typically takes less than ten seconds. Alternatively, if a user has limited mobility, the sensors can be initialized before the shirt is pulled on. The BNO055 sensors are able to provide an initialisation score that can be used to monitor and guide this process.

13.2. User test: fit, comfort, and user experience

Next to assessing the visualisation performance of Movi, it is also needed to reflect on the overall design of the shirt. This was done with a user test focusing on fit, comfortability, understandability and user experience of the smart shirt and visualisation. The findings from this test are intended to evaluate the design and guide recommendations to enhance the shirt's design.

Methodology
The user test was split in the following sections: pulling on, fit, comfort, visualisation and user experience. For assessing comfort the method of Body region discomfort was selected from Anjani et al. (2020), and adjusted for the upper body. For assessing user experience the User Experience Qualities method (User Experience Questionnaire (UEQ), n.d.) was used. A small booklet was used for leading the test and giving feedback, while the participants were asked to talk out loud. For the detailed user test set up refer to Appendix N.

Participants
The user test was conducted with five participants, see Figure 74. They were recruited from researchers personal network, because the prototype is not yet developed enough to apply for medical testing. Selecting participants on shirt sizes up till medium, because otherwise they would not fit the shirt. The participants were of a quite homogeneous group, they had around the same age, cultural background and educational level. This means the results form this test do not represent the actual, full rehabilitation target group. However, the smart shirt is first proof-of-concept and therefore feedback from a small group without rehabilitation needs already gives valuable insights.

Participant ID	age	gender (f/m/x)	nationality	smart wear experience	sport shirt size (xs/s/m/l/xl)
participant 1	26	f	Dutch	none	m
participant 2	26	m	Spanish	none	m
participant 3	24	f	Dutch	none	s
participant 4	24	f	Dutch	none	m
participant 5	24	f	Dutch	none	m

Figure 74. *User test participants and their characteristics*

Figure 75. *User test participants and their characteristics*

Results
A summary of the results and insights are presented here, for all the results refer to Appendix N.

Quick & easy to pull on - The difficulty of pulling the shirt on was rated a 2.8 on 7 point scale from easy to difficult. The tightness of the shirt was stated to be hardest when pulling the shirt on. However, the stretch was also stated to be enough to make pulling the shirt on possible. Participant 5 stated that they expected the snug fit, because of the thermo-like aesthetics of the shirt.

Turned IMU on lower arm - The sensors on the back and on the upper arms immediately were on their meant place with every participant after putting the shirt on. It was observed that the IMU on the, especially right, lower arm ended up on the inner part of the arm when the shirt was put on and needed to be turned to the top of the arm.

Snug fit - The fit of the shirt is rated an average of 5.4. The shirt fitted quite well with all female participants, while the shirt was way tighter for the male participant, especially around the upper arms, wrists and the shoulders.

Long sleeves - Participant 2, 3 and 4 experienced the sleeves to be to long. The anti-slip band around the wrist ended on the hand by participants with shorter arms. Participant 3 found the shirt to long, while participant 5 liked the long fit especially, because then it wont curl upwards and makes it more comfortable for women with larger breast.

Overall Comfortable - The shirt was rated 5.6 for overall comfort. Additionally, the comfort for extended wear received an average rating of 4.8. Participants 3 and 4 rated extended wear the same as overall comfort, while the other participants gave lower ratings, citing tightness as the reason.

Minor discomfort points - The results for areas of discomfort are combined in Figure 56. The intensity of all discomfort points was rated 4 or lower. Most points were on the outside of the arms and upper back. Two participants found the anti-slip feature around the wrists uncomfortable, rating it a 4, the highest discomfort level overall. Participant 4 mentioned that the shirt pulled slightly on the shoulder blades. Two participants noted feeling the sensors on the back, while one mentioned that the sensors fit nicely between the shoulder blades.

Intuitive visualisation & interface - All participants quickly understood that the armature on screen mirrored their upper body movements and linked the armature's parts to their corresponding body parts.

Four out of five participants suggested making the mannequin more human-like by adding features like a head, hands, and hips. One participant preferred the technical design for better information, such as angles between the arms. Two others felt a clearer distinction between the front and back of the armature and multiple viewpoints would help in understanding the arm movements.

Participants also gave feedback on the interface. One said they focused 90% of their attention on the armature but wanted more clarity on the menus, while another suggested adding a background to help the armature stand out.

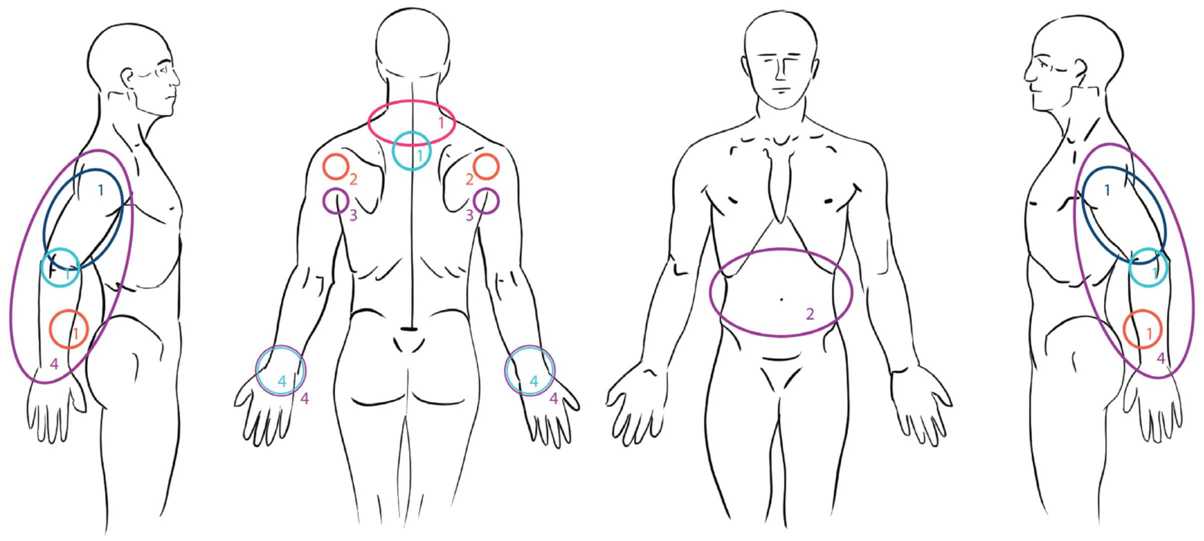


Figure 76. *A summary of all named discomfort points and their rated intensities*

Interacting with the visualisation - Participants tested the system by trying out different movements, like squats and side steps, but noticed that the visualization didn't adjust to these actions. Participants 2 and 4 pushed the limits by performing extreme movements and making the sensors touch each other (see Figure 78).

Participant 2 got creative with boxing moves, Participant 1 waved their arms, and Participant 4 added clapping, dance, and robot-like motions (see Figure 77).

Future use ideas - The visualization could help users spot differences between the left and right sides of their bodies, allowing them to focus on strengthening the weaker side. It could also motivate users to perform exercises correctly, either by following along with an armature or tracking progress with scores.

"I'd like more instructions on what to do in front of the screen," said Participant 3. Participant 2 also saw potential for using the tool to find exercises for injuries and suggested having online physiotherapy consultations.

Figure 77. *Participant doing robot moves while using Movi*

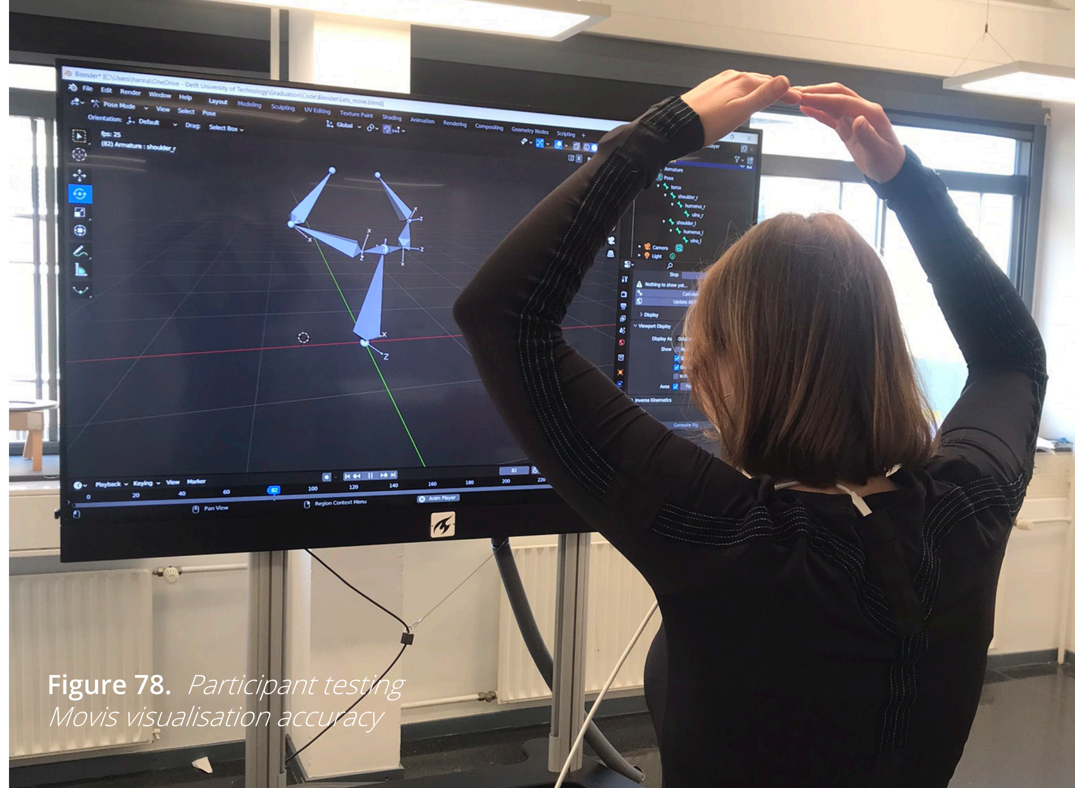


Figure 78. *Participant testing Movis visualisation accuracy*

Positive user experience. As shown in Figure 59, all the UEQ ratings were overwhelmingly positive, highlighting an overall great user experience.

Excitement & engagement .The level of excitement users experience seems to depend on their personal background and prior exposure to similar technology.

"I think young people would immediately connect this shirt to the Wii or Just Dance, but older users might be more impressed and surprised by the technology." – Participant 2

"Over time, though, I think the novelty will wear off and the excitement will fade." – Participant 2

Effect of electronics on comfort. While the integration of electronics into the shirt was largely seen as seamless, some discomfort arose when plugging in the USB-C cable while wearing it. Four out of five participants noted feeling surprised or even like they were "becoming a robot."

"It's a strange feeling, getting plugged into myself!" – Participant 5

On the positive side, the clean integration of the electronics was well-received.

"Honestly, having the electronics integrated so smoothly into the shirt made me feel much more comfortable. When I think of medical devices, I expect to see a mess of cables or bulky equipment, but this feels much more streamlined." – Participant 2

Personal Connection . The armature's ability to mirror the user's movements created a sense of connection. Participants felt like it was a reflection of themselves, which motivated them to do the exercises correctly.

"Hey, that's me! I'd want to take care of my little figure." – Yara

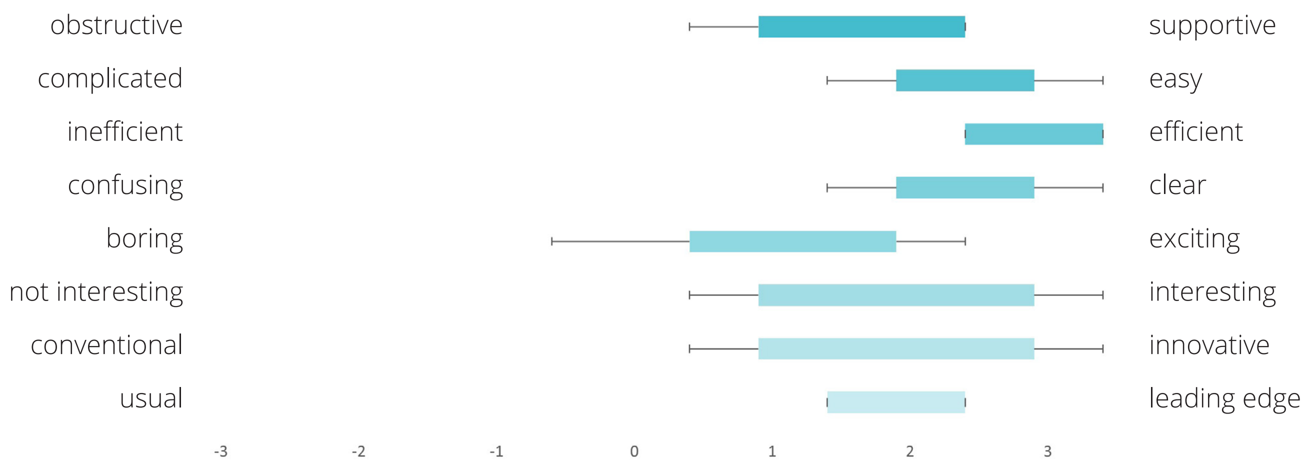


Figure 79. *Boxplot of the UEQ ratings of the smart shirt*

Discussion

The results showed that the lower arm IMUs need a small adjustment after pulling the shirt on. Telling the user before that the blue lines should be on top of the wrist, they will know this and this will not be a problem. The sleeves are long, which did cause that the user needs to adjust the sensor on the lower arm and move it a bit higher up the arm. This is not a problem because the user already needs to adjust the lower sensor placement.

The fit of the shirt resulted to be correct for women with shirt size small and medium. The shirt was to tight for the male participant (shirt size medium), he also noted most discomfort points and it was observed that he had difficulty with pulling the shirt on and of. Making a shirt directed especially to men would be useful.

The shirt is overall quite comfortable. It does cause some discomfort around the wrists. The anti-slip around the wrists is to tight for some and could itch and cause discomfort overtime, which should be looked at. Furthermore, the sensors and the wires are felt but this discomfort is minor and therefore no problem. The shirt is quite thick and therefore warm, but this was needed to integrate the sensors stable and robust.

The high UEQ ratings show that the overall experience is a simple, exciting experience. The fact that users started experimenting with movements on the screen without being asked shows that it is inviting and stimulating. The simplicity is also named by the participants as one of the unique qualities and the fact that the participants all understood the visualisation without additional explanation underlines this.

Additionally, during the test phase, multiple users pulled the shirt on, used it, and removed it without the designer's help, including for tasks like making the video and taking pictures for this report. This indicates that the shirt is robust, as it did not break or malfunction during these processes.

Key takeaways

Movement visualisation performance

- The visualization tracks movements in real-time and remains stable during a 30-minute session.
- However, there is an offset between the user's pose and the visualization, likely due to incorrect IMU starting point correction. This is acceptable for gamified exercises but may affect diagnostic accuracy. A proper calibration method could improve this.
- The noticeable delay in visualization was solved by increasing the sample rate of the IMU data to 100Hz.
- The IMU initialisation should be part of the user flow, with a prompt for brief movement to complete the setup.
- For users with limited mobility, the sensors can be initialized before wearing the shirt.

User test

- The IMU on the lower arm needs to be manually adjusted by the user to be placed correctly.
- The fit is good for women in sizes S and M.
- Movi is generally comfortable, but the wrist anti-slip feature causes discomfort and should be reconsidered.
- Users understand that the visualization reflects their own movements.
- The visualisation encourages interaction.
- Identifying with the avatar can increase the motivation to do exercises. Many participants also preferred the armature to look more human-like.

Expert feedback on showcase video

- *"Surely an interesting direction for in the future!"* - Janse, advisor innovation at Basalt

Figure 80. *Movi branding*

14. Discussion

This last chapter of the report discusses the project outcome. It includes a final conclusion with limitations, recommendations for future work, and a personal reflection on my process during this thesis project.

14.1. Final conclusion

The project

The main goal of the project was to create a proof-of-concept for an **accessible** smart shirt that integrates IMUs into a single garment to **capture and visualise upper body movements** for physical rehabilitation.

This objective was successfully achieved, with the prototype functioning as intended to track movements and provide a real-time visualisation during rehabilitation exercises. Significant time and effort were dedicated to creating the prototype and addressing practical challenges associated with integrating the technology into a wearable garment and making a real-time visualisation.

Extensive research and development went into the integration of the electronics into the shirt to improve comfort and usability. The goal was to move away from the concept of small, separate bands that needed precise placement. The final design integrates the electronics more seamlessly into the shirt, making it more compact and comfortable than previous prototypes, such as Alamel et al. (2024).

Lastly, the project focused on accessibility, which was tackled by lowering the cost and designing the shirt to be easy to put on. By minimising the setup requirements, the prototype eliminates the need for expert assistance, allowing patients to use it independently at home.

Value of Movi

The primary focus of Movi was creating a real-time visualisation tool for at-home exercises, providing immediate feedback to help patients perform their rehabilitation exercises effectively. In the future, this system could be expanded to incorporate biofeedback for error-less learning, guiding patients to perform exercises correctly without errors. Additionally, the system could gather data on patients' movements throughout the day, enhancing monitoring and feedback in a broader context beyond just in-home exercises.

Movi demonstrates the feasibility of a motion capture system that integrates IMU-based technology with the practical needs of patients and rehabilitation specialists. Unlike current research, which often prioritizes motion capture accuracy or targets high-end markets like gaming and film (Xsens, 2025), Movi takes a more holistic approach by focusing on accessibility and ease of use. It ensures that the technology is functional, easy for patients to use independently, and does not require expert assistance. A key part of the design was integrating the electronics in a comfortable way, securely placing the sensors without compromising the wearer's comfort. Furthermore, Movi serves as a therapeutic tool, adding value to existing literature, as Gu et al. (2023) found that most research focused on rehabilitation assessment (82%).

This prototype demonstrates the potential of using a motion capture garment as a patient-centred tool, bringing it closer to practical use in rehabilitation. Moreover, it is significantly cheaper than most current research projects and far more affordable than commercial IMU motion capture systems like Xsens (2025), making it accessible to a wider range of patients and rehabilitation centres. Movi could reduce the overall cost of rehabilitation by decreasing the need for frequent clinic visits and allowing for continuous monitoring from home.

Movi has the potential to adjust to various rehabilitation applications, including sports recovery. Future developments could expand to monitor muscle strength, joint flexibility, and posture.

Limitations of Movi
The current concept and prototype have several limitations that impact its performance and usability.

Limited movement capture
The motion capture in Movi is based on rotational data, which limits the types of movements that can be captured. A rotation of the armature around the z-axis could represent either a torso rotation or a rotation of the entire body in real life, making it difficult to distinguish between these actions. Similarly, walking, moving up or down, or bending the knees will not change the visualisation, as Movi does not track position, only rotation. This limits Movi's capabilities for capturing more complex motion patterns.

Limited precision
Movi currently uses a standardised rotation as a calibration process, which reduces the accuracy of the motion capture. Sensor placement differences between users or sessions, along with minor displacements during use, are not corrected. This can result in inconsistent data across sessions or between individuals, limiting precision and reliability.

Fit dependence
The design of Movi depends on a snug fit to keep the IMUs securely in place. This creates challenges in accommodating varied body shapes. The shirt must consider not only length but also width to maintain proper sensor alignment. For users with extreme body types, either very slim or broad, the shirt may fit too loosely or too tightly, causing discomfort or sensor misalignment.

14.2. Recommendations

This section outlines key recommendations for enhancing the smart shirt design and suggests areas for further research.

User Interaction Study
Future research should investigate how users engage with both the smart shirt and its accompanying screen interface. Key aspects to explore include the optimal placement of interaction points on the shirt and ensuring that connecting, adjusting, and wearing the shirt is intuitive and user-friendly for individuals with varying levels of mobility. Conducting a user interaction study involving actual patients and rehabilitation specialists is strongly recommended to gather realistic, practical insights that reflect real-world use.

Waterproofing
To ensure the shirt remains clean and durable, further development is needed to make the electronic components waterproof. One option is to encapsulate the electronics and use a waterproof connector for the microcontroller. This would allow the microcontroller to be detached for maintenance or washing, without compromising water resistance.

Calibration Process
The performance evaluation revealed that calibration is essential for accurate visualization. However, due to limited mobility in patients, traditional calibration poses are not feasible. Research is needed to develop an alternative calibration method that accommodates a wide range of mobility levels, or to design a system that minimizes the need for calibration altogether.

Develop User-Centric Visualization Software
The current visualization tool is not yet suitable for practical use by patients or rehabilitation specialists. A dedicated application or software platform should be developed, specifically tailored to meet the needs of these target users.
This tool should offer key features such as: Exercise session tracking, Data storage and retrieval or Customization options informed by feedback from medical professionals

Additionally, improving the visualisation of the avatar is crucial. The avatar should be connected to the armature system in Blender to ensure accurate, responsive movement representation. It is important that the avatar not only clearly displays the user's physical movements but also fosters a sense of personal connection. Based on user testing, making the avatar more human-like is a desired improvement.

Simplify the Physical Shirt Design
Consider designing a new shirt from the ground up, rather than modifying existing garments. Improvements should include:

- Removing bulky connectors from the BNO055 sensors
- Eliminating unnecessary anti-slip features on the wrists
- Reducing the size of the electronic components
- Removing the need for a multiplexer by adopting software solutions (as demonstrated in the Smart Suit project by Acans et al.(2021)) that allow for direct sensor integration

Wireless connectivity
A future prototype should incorporate wireless connectivity, which was not achieved in the current project phase. Adding wireless functionality will significantly enhance user comfort and freedom of movement, eliminating the discomfort caused by plugging in a USB-C cable while wearing the shirt.

Explore applications and use cases
Further research should focus on how the smart shirt and visualisation system can be most effectively integrated into rehabilitation routines. This includes defining specific use cases, determining the most beneficial exercises, and understanding how best to support both patients and therapists in their goals.

14.3. Personal reflection

Looking back at this project, I realise how much I have learned throughout the process.

I gained valuable new skills, such as learning to solder, working with electronics, and integrating these with programming and visualisation tools. I also used Blender for the first time, which was a rewarding challenge.

What I enjoyed most was building the prototype. It was satisfying to see my ideas come to life, and testing it was an insightful experience, with participants offering unexpected insights and enthusiasm.

Managing the project on my own was both exciting and challenging. I had to trust my decisions and direction, which came with its difficulties. The most valuable takeaway for me is that I have to zoom out once in a while. I always reflect on what could have been better, but seeing the project as a whole I am proud of the working prototype I have created.

Reflecting on myself as a designer, I think I would say I am someone with an analytical eye that likes to dive into a subject and tries to solve problems in a hands-on manner. However, I also want to keep in touch with the added value a design can bring. This is hopefully something I will keep on doing in the future.

Hannah

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