

# Kinetik

Development of a textile strain sensor wearable for continuous knee flexion monitoring in rehabilitation

Nienke Ickenroth

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**Author**

Nienke Ickenroth

**Master Thesis**

Delft University of Technology  
Faculty of Industrial design Engineering  
MSc Integrated Product Design  
February 2026

**Supervisory team**

*Chair*  
Prof. dr. ir. Kaspar Jansen  
Department Sustainable Design Engineering,  
Section Emerging Materials

*Mentor*

Ir. Anna Ruiters  
Department Human-Centred Design,  
Section Human Factors

# Preface

Dear reader,

This report describes my 20-week graduation project and concludes my studies at the Faculty of Industrial Design Engineering. I chose this project because I find the interaction between technology and human experience very interesting, especially in contexts where design can have a real impact on people's well-being. Around me, I see a growing interest in tracking health and performance using wearable devices like sports watches and fitness trackers. The growing use of these self-monitoring devices made me wonder how similar technology could be applied in an even more meaningful healthcare context. The opportunity to develop an accessible and affordable solution using an innovative stretch sensor, which is capable of generating valuable data in a simple way, seemed very interesting to me.

At the same time, I chose this project as a challenge. My prior knowledge of textiles, electronics, and data collection was limited, and I saw this as an opportunity to expand my technical skills while still keeping a human-centered design approach.

I would like to thank my supervisors; Kaspar for always being willing to share and discuss ideas and results with the technical aspects of my project, and Anna for her support regarding the usability aspects and her valuable, comprehensive feedback. The combination of these expertises has helped me in every aspect of the project and led to many valuable discussions.

I would also like to thank Marciano from Roelfsma Physical therapy for his valuable insights, the opportunity to test my product in practice, and for ans-

wering my questions about the rehabilitation sector anytime. Finally, I would like to thank everyone who was involved in this project and helped me: the orthopedist and patients who were willing to share their knowledge and experiences with me, the staff at the applied labs who were always available when I needed help, and friends, family, and participants who contributed ideas, held discussions, and/or volunteered to participate in tests and interviews. With everyone's support, this project has grown into a valuable project.

*This report was written entirely by myself. AI was used to a limited extent to support brainstorming ideas, refining some of formulations and support in python coding.*

I hope this report interests you and offers valuable insights and inspiration.

*Nienke Ickenroth*

# Summary

This graduation project focused on developing a functional, comfortable, and reliable textile knee sensor sleeve for use in rehabilitation after knee injuries. Knee injuries are common and have a big impact on daily life. Current progress measurements in knee rehabilitation are mainly based on subjective observations by physical therapists. Objective measurements, when performed, are often fragmented, limited to snapshots, time-consuming and presented in difficult-to-interpret data. This results in a lack of continuous insight into movement of the knee, which makes it difficult to monitor and evaluate progress during exercises and throughout the entire rehabilitation process.

The research focused on the use of textile strain sensors as an accessible and affordable alternative to more complex and expensive sensors like IMUs. These sensors detect strain via changes in contact points, enabling to track movements like joint flexion (bending) and extension (stretching). Because of the high number of knee injuries and the impact on daily life, where the knee is constantly under strain during movement, this joint was chosen as the focus of this project.

To optimize the design for both technical and user-friendliness, the project combined literature research, field research, experimental research, and user testing. This provided insight into user needs, technical constraints, and optimizations for the sensor. The concept was developed by integrating the sensor and associated electronics into a textile knee sleeve and investigating how knee movement influences the sensor output. A visual interface was also developed that presents the data to the user in an understandable way. Design choices were validated through feedback from potential users, measurements, and iterative testing.

The result of this project is KinetiK, a knee sleeve and accompanying interface that allows users to monitor their movements in real time via a live graph. Instant feedback allows users to improve and correct their exercise performance during the session. The interface also gives an overview of session results, such as the number of bends, movement consistency, and maximum flexion angle. Long-term trends and badges help the user track progress and achieve goals. User testing confirmed that the concept is valuable for both patients and physical therapists, as it provides insight into progress and increases motivation.

Validation tests show that the knee sleeve is currently capable of counting the number of flexions, estimating maximum knee angles, measuring movement consistency, and tracking range of motion symmetry. However, precise measurements of knee angles and movement symmetry need additional research and optimization.

All in all, this project shows that a textile knee sensor sleeve can be a useful, accessible, and motivating rehabilitation tool, with potential for further application in for example daily activity monitoring, as motivational game-based application, and future use in combination with other sensor technologies. The project combines technology with user-centered design and gives a solid foundation for further development of a desired data-driven rehabilitation aid.

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# PROJECT OUTLINE

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This phase introduces the project and explains how it will be approached.

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1. Project introduction
2. Project approach

*Figure 1*  
A snapshot of the manufacturing process of the knee sensor sleeve, where the sensor is sewn onto the fabric with preset parameters.



Figure 2 A physical therapist examining the patients knee (POPB, 2024)

# 1. Project introduction

This chapter introduces the topic and discusses the stakeholders within the current rehabilitation system and the sensor technique used within this project.

- 1.1 Subject introduction
- 1.2 Stakeholders
- 1.3 The technique

## 1.1 Subject introduction

The knee is one of the most complex and most stressed joints in the human body. It includes multiple ligaments, menisci, and cartilage structures that together ensure stability and mobility. The joint plays an important role in doing everyday activities like walking, climbing stairs, and standing. Damage can cause instability, pain, and functional limitations (Hurmuz et al., 2025)(Klasan et al., 2024). These knee injuries often need surgery and long rehabilitation (Prill et al., 2021).

In the healthcare, these patients are guided by physical therapists and orthopedists after knee surgery. The recovery progress is assessed with observations during clinical checkups. However, these measurements only provide snapshots of the recovery process and lack continuity and objectivity. These are important for a clear picture of the entire recovery process.

At the same time, innovation is taking place in the development of smart textiles and e-textile systems, in which sensors connected by conductive yarns, are integrated into clothing and wearables. These make continuous monitoring of functions possible like heart rate, body temperature, and movement (Sipos et al., 2025)(Meena et al., 2023). In addition, these systems have the advantage of unobtrusive, comfortable, and potentially long-term monitoring both inside and outside the clinic (Zaman et al., 2021)(Lu et al., 2024). These wearable sensors are interesting for monitoring the movement of the knee, but their integration into clinical practice has barely been investigated and an accessible and affordable option has not been developed (Prill et al., 2021)(Small et al., 2019)(King et al., 2022).

Textile-based strain sensors offer an innovative way for measuring strain. They are particularly useful for monitoring flexion, which induces strain, making them interesting for tracking movements of joints like the knee.

This project aims to develop a functional, comfortable and reliable textile knee sensor sleeve, consisting of an integrated strain sensor that can continuously measure knee flexion during rehabilitation exercises.

The design focuses on:

1. The sensor's technical performance (material selection, yarn selection, pattern design)
2. User comfort and integration (stability during wear, placement on the knee, comfort during wear, sleeve design)
3. Interface integration (translation of raw data to understandable information in a visualised interface)
4. Relevance within the rehabilitation context (real-time monitoring, long term monitoring progress overviews).

This innovation can be valuable for multiple stakeholders. For patients, it gives better insight into their status and progress, which can increase motivation and engagement in the recovery process. For physical therapists and orthopedists, it gives objective and continuous data that can assist them in treatment.

## 1.2 Stakeholders

Various stakeholders are involved in bringing the textile knee sensor sleeve into practice, each in their own way (Figure 3). They each have their own interests, needs, and expectations regarding the product. It is important to understand these perspectives so that the design meets these needs and expectations and can be used effectively in the rehabilitation process.

### Patient

The patient will be the primary user of the knee sensor sleeve. Their role is the most important because they wear and use the product during the rehabilitation process. Their goal is to rehabilitate as quickly as possible and return to normal life or sport. For them, it is important that the knee sleeve is comfortable, easy to use, and gives reliable and helpful measurements. The data can make progress more tangible and give them insight into their progress. Visual feedback or measurement results can also be motivating.

### Physical therapist (PT)

The physical therapist guides the patient during the rehabilitation process and can use the data generated by the sensor to assess rehabilitation progress and adjust the rehabilitation plan when needed. Live monitoring can directly give feedback during exercises and easily interpretable data can offer clear insight into progress, allowing the entire recovery process to be reviewed.

### Friends and family

Friends and family give emotional support to the patient and play an important role in motivating them during the recovery process. They can encourage the use of the knee sensor sleeve and in that way contribute to consistent rehabilitation. Their involvement can increase the likelihood that the patient will stay motivated to actively work on their recovery.

### Orthopedist

The orthopedist performs the knee surgery and keeps an eye on the patient's medical recovery. Data from the knee sensor sleeve can give objective insight into the overall knee function and recovery. This can help the orthopedist evaluate the surgery success and determine whether adjustments to treatment or a revision surgery are needed.

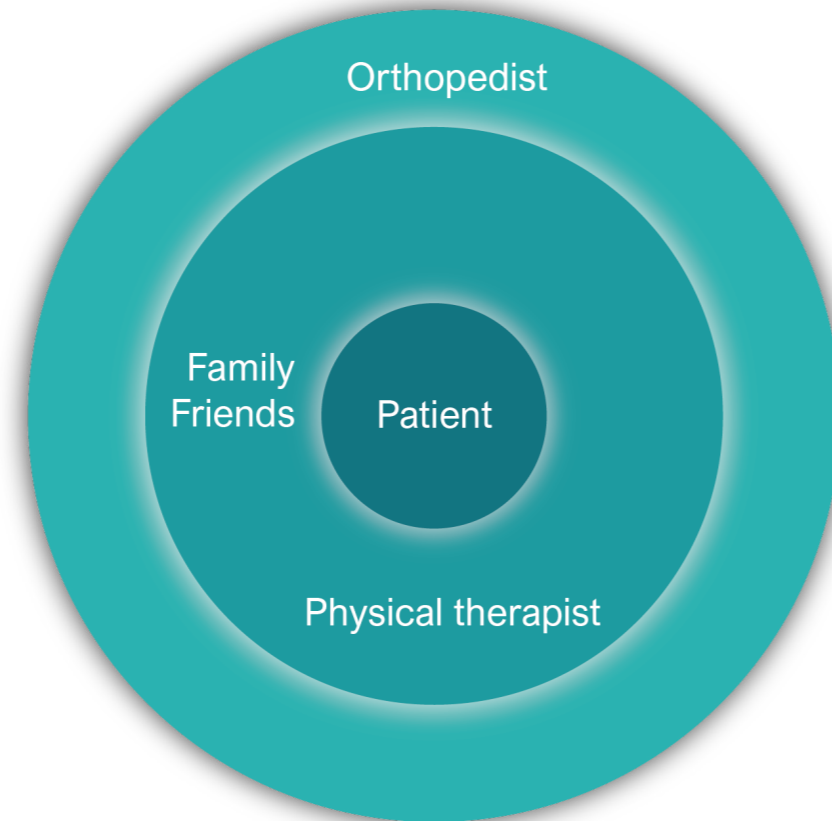


Figure 3. Current stakeholder map of the rehabilitation system

## 1.3 The technique

An innovative way to measure movement is through conductive yarn patterns, integrated into textiles by knitting or embroidering/sewing (Bozali et al., 2022)(Tseghai et al., 2020)(Jansen, 2020). These conductive yarns detect stretch by changes in electrical resistance. This change in resistance can monitor the movement (flexion and extension) of joints (Kim et al., 2024).

When the sensor is stretched, the conductive yarn loops gradually get separate, which reduces the number of contact points between the loops (Figure 4). This change in contact resistance can be translated into the movement (bending) of the knee (Jansen, 2020).

The primary goal in developing textile strain sensors is to create a measurable and reliable change in electrical resistance in response to stretch. In a relaxed state, the fibers should touch each other at multiple points to create a direct path, resulting in a low resistance. Upon stretching, these contact points should disappear or weaken, resulting in a measurable increase in resistance.

They offer several advantages over traditional solid sensors, including low cost, lightness, and adaptability to the human anatomy in combination with the strain-sensing functionality (Bozali et al., 2022).

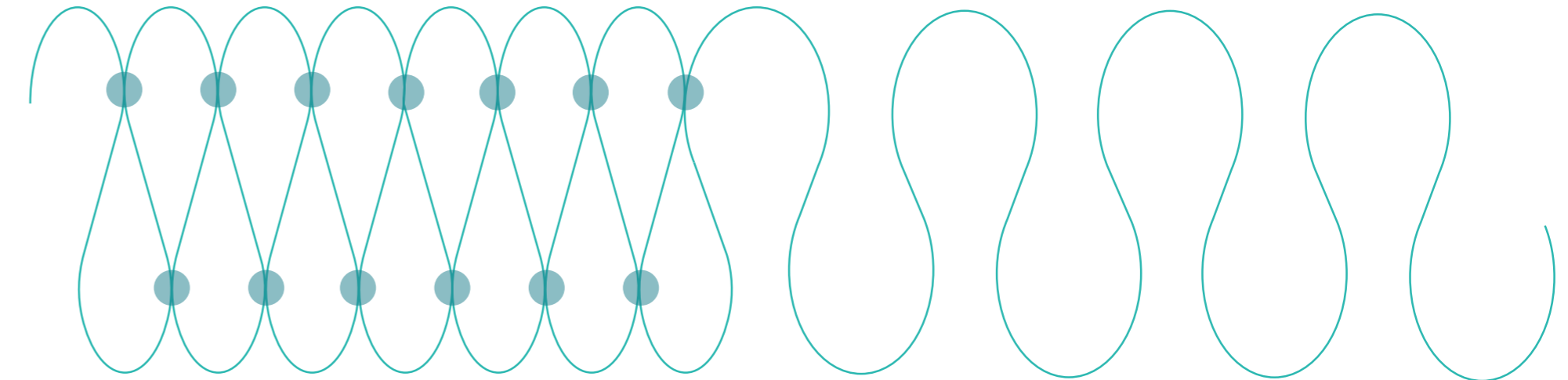


Figure 4. The strain sensor mechanism: the left side illustrates the sensor yarn in its relaxed state, where contact points are present, while the right side shows how these contact points disappear when the sensor is stretched.



Figure 5.  
A warm-up for the project

## 2. Project approach

This chapter discusses the design process and the methods used and describes the assignment with the desired outcome.

### 2.1 Process and methods

#### 2.2 Test participants

## 2.1 Process and methods

Within this project, the Double Diamond method was used as the base for the design process. This method consists of four phases: Discover, Define, Develop, and Deliver, each with its own focus (Figure 6). Within this structure, both standard methods from the Delft Design Guide (Van Boeijen et al., 2020) and own methods were used to systematically address the various phases and sub-phases.

### Discover

The Discover phase was approached by dividing the research into three parts in order to gather the necessary knowledge and insights.

- **Literature research** was conducted to investigate the anatomy and movement of the knee, existing knee braces, sensor technologies, production processes and data processing. This provided a solid foundation of technical and theoretical knowledge that supports the design of the sensor and the way the data will need to be processed.
- **Field research** consisted of expert interviews with two patients, a physical therapist, and an orthopedist to gain insight into the rehabilitation process, user needs, and requirements from both the patient and healthcare perspectives. This data ensures that the design is in line with the practice and user experience.
- **Experimental research** was conducted by testing varying fabrics, yarns, and patterns with a LETT meter with resistance measurement. The materials were assessed on variables like sensitivity, linearity, and repeatability. This research gave practical insights that informed the sensor design.

### Define

During the Define phase, the findings from the Discover phase were translated into a clear design direction. **Patient Journey Mapping** was used to visualize the rehabilitation experience, which helped to determine where the knee sensor sleeve could offer the most value. Based on this, a **Problem Definition** was formulated and a **List of Requirements** was made, which focuses mainly on function, ergonomics, and technique. This step gave direction and created a framework within the design process took place.

### Develop

The Develop phase focused on developing the design into a functional prototype. This phase was carried out in iterations, with testing and discussions which led to targeted well-considered choices and adjustments to optimize both the technical operation and user experience of the knee sensor sleeve.

Technical choices, like the integration of the strain sensor and the connection between the sensor and electronics, were tested and evaluated using sensor measurements.

User-oriented choices, like comfort, fit, prevention of shift, positioning instructions, and the appearance of the sleeve were investigated using prototypes, tests with participants, and discussions with users. The gathered feedback was used to further improve the design, to ensure that the sleeve is both functional and user-friendly.

### Deliver

In the Deliver phase, the design and interface were finalized, presented and evaluated. The final design is explained by showing its parts in the order of its production process and its associated interface is explained by visualised screenpages. The final knee sensor sleeve is tested in real-life situations to validate both its measurement functionality and wearing comfort.

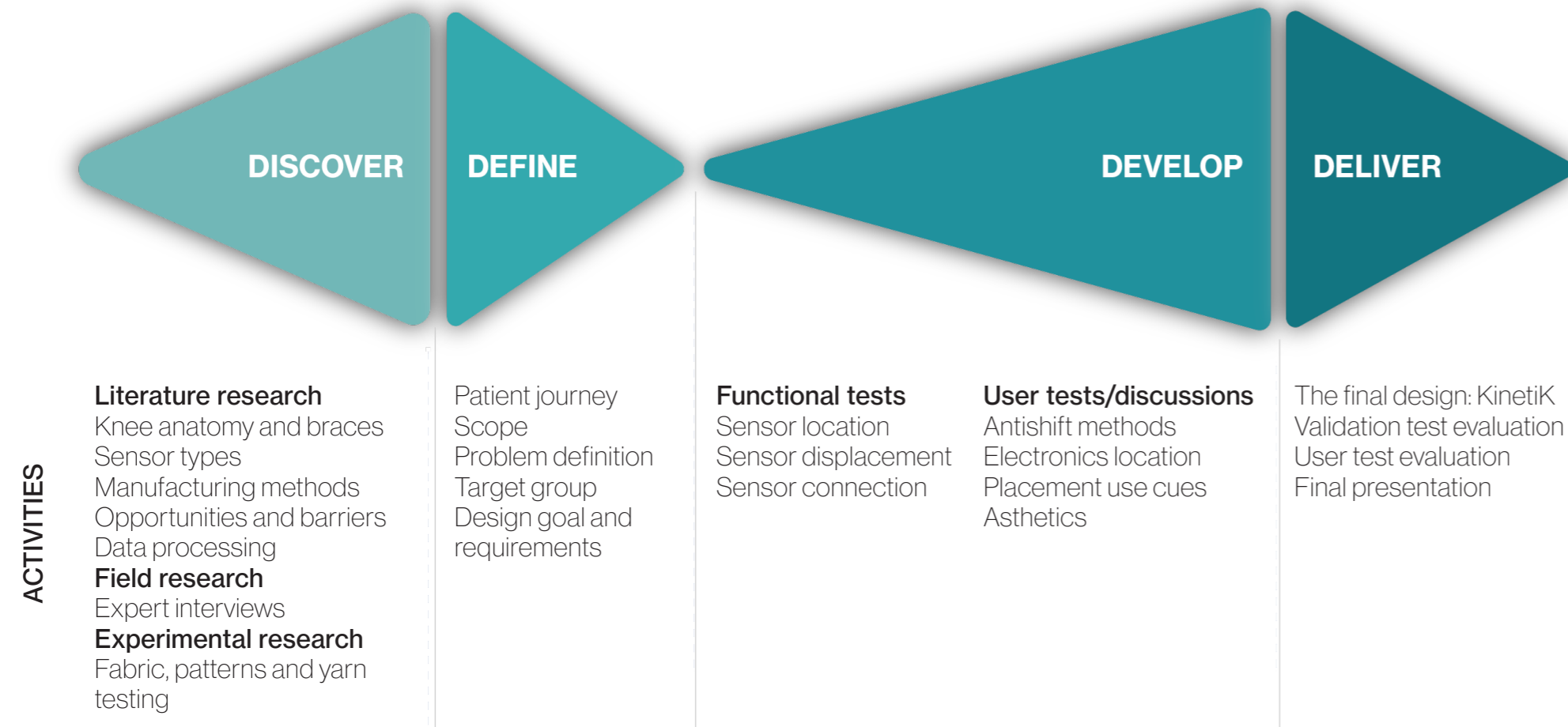


Figure 6. This visualisation shows the double diamond technique including the activities performed per phase.

## ASSIGNMENT

This project investigates how textile-based, stretch-sensitive sensors can be used to measure knee flexion in an accessible and comfortable way. Many existing measurement solutions, like IMUs, are accurate but complex, prone to drift, and less suitable for daily use outside the clinic. Therefore, conductive yarns integrated into a knee sleeve will be investigated. The goal is to discover whether these sensors are reliable, reproducible, and practical for wearing on the knee during rehabilitation exercises. In addition to technical performance, user experience is also being investigated, like wearing comfort, positioning, and comprehensibility of measurements for both patients and healthcare providers.

## DESIRED OUTCOME

The prototype does not prioritize maximum precision, but rather focuses on being functional, accessible and comfortable. By combining technical validation with input from rehabilitation patients and healthcare providers, the wearable gives insights into movement, patterns and changes over time. The end result is an accessible tool that supports and motivates patients, promotes adherence throughout the rehabilitation process, and enables them and healthcare providers to be able to view and understand the rehabilitation progress.

## 2.2 Test participants

The project starts with interviews with patients, a physical therapist, and an orthopedist to gain more insight into the rehabilitation process from various perspectives and to assess the potential of the knee sensor sleeve.

In the final phase, the usability and comfort of the concept will be evaluated through extensive user testing.

The interviews and tests conducted between these, aimed at evaluating the usability and comfort of specific elements and substantiating design choices, were conducted with students from the Faculty of Industrial Design Engineering. This group does not fully represent the patient population, as they lack experience with rehabilitation. However, within the short timeframe of the project, working with students allowed for quick and efficient evaluation of decisions, without constantly interrupting the process to wait for patients to become available.

Although design students lack direct experience with rehabilitation, they are still valuable for testing design decisions because they are critical and analytical and can usually well empathize with a user's situation. In addition, the majority of patients undergoing knee rehabilitation, have had an anterior cruciate ligament (ACL) surgery. These surgeries are usually performed up to around the age of 25, which means the student age group reflects a relevant part of the target population.

The interim tests were therefore conducted with this group of students. Unless otherwise stated, these students will be referred to as "the participants" in the subsequent descriptions of the interim tests.



# PHASE 1

## DISCOVER

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In this phase, literature, field and experimental research is conducted to gain more insight into the chosen technique, manufacturing options, optimal sensor variables and the rehabilitation system and users.

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- 3. Literature research
- 4. Experimental research
- 5. Field research

*Figure 7*  
The manufacturing of a textile strain sensor,  
where the yarn is sewn onto the fabric with  
preset parameters.



## 3. Literature research

This chapter uses literature research to delve deeper into the knee and knee braces, existing sensors, production techniques and data processing.

- 3.1 Knee anatomy
- 3.2 Strain sensors vs other sensors
- 3.3 Opportunities and barriers
- 3.4 Knee braces
- 3.5 Manufacturing methods
- 3.6 Data processing

### 3.1 Knee anatomy

The knee is a complex hinge joint which consist of the femur (thigh bone), tibia (shin bone), and patella (kneecap)(Figure 9)(Prathap Kumar et al., 2020). The joint can move in six directions: flexion and extension (bending and stretching), abduction and adduction (sideways movements), and internal and external rotation (Gray et al., 2019).

In this project, the focus is on flexion and extension. Knee flexion is important in rehabilitation because it is directly related to recovery and pain reduction. An increase in knee flexion after an injury or surgery is associated with less pain and better daily functionality, like walking, climbing stairs, or getting up from a chair. It is an important outcome measure because an improving range of motion is a sign for strength building, coordination, and return to normal mobility.

To measure knee flexion, the strain sensor will be placed on the front of the knee, since this location gives the most pronounced and consistent stretch of the fabric during flexion and extension (Xu et al., 2021). When the knee bends, the skin and fabric at the front of the joint undergo tensile stress, which can be recorded by a strain sensor.

Placing the sensor at the back of the knee is less suitable, as knee flexion in this area mainly results in compression and folding of the fabric instead of stretching.

Other movement directions, like varus-valgus movements (inward and outward tilting of the knee) or rotational movements in the frontal and transverse planes, are not included in this design. These movements originate mainly in the hip joint and are less directly expressed as tensile strain around the knee, making them unsuitable for measuring with a strain sensor.

Femur (thigh bone)

Patella (knee cap)

Tibia (shin bone)

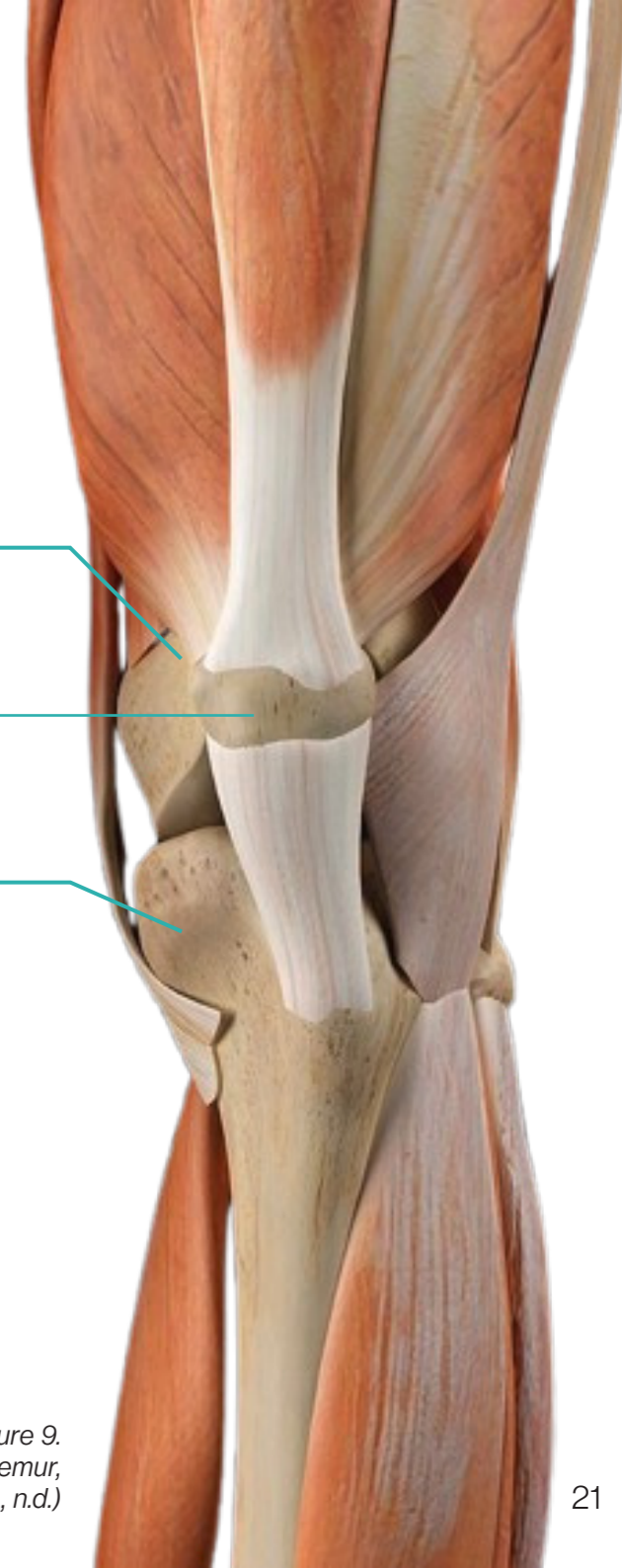


Figure 9.  
The knee showing the location of the femur, patella and tibia (Science Photo Library., n.d.)

## 3.2 Strain sensor vs other sensors

There are various sensor technologies for measuring knee flexion and extension, each with its own way of operating, advantages, and limitations. The most common used systems in research and practice are Inertial Measurement Units (IMUs), flex sensors, and potentiometers (Figure 10).

IMUs combine accelerometers, gyroscopes, and sometimes magnetometers to calculate the relative orientation of body parts (Figure 11)(Antunes et al., 2021)(Ajdarski et al., 2020)(Fennema et al., 2018)(Stetter et al., 2020). In general, these sensors have a high accuracy ( $\pm 1^\circ$  to  $\pm 8^\circ$ ) and can record movements in multiple directions. Disadvantages are its sensitivity to noise and drift, the use of complex algorithms like Madgwick or Kalman filters, and being a hard component, which can influence comfort (Bozali et al., 2023) (Huang et al., 2022b).

Flex sensors and potentiometers measure angles based on change in resistance (Gitau & Ciira wa Maina, 2022)(Bakhshi & Mahoor, 2011)(Büttner et al., 2021)(Toffola et al., 2012). They are affordable, easy to use, and suitable for cases where only one direction of movement needs to be measured.

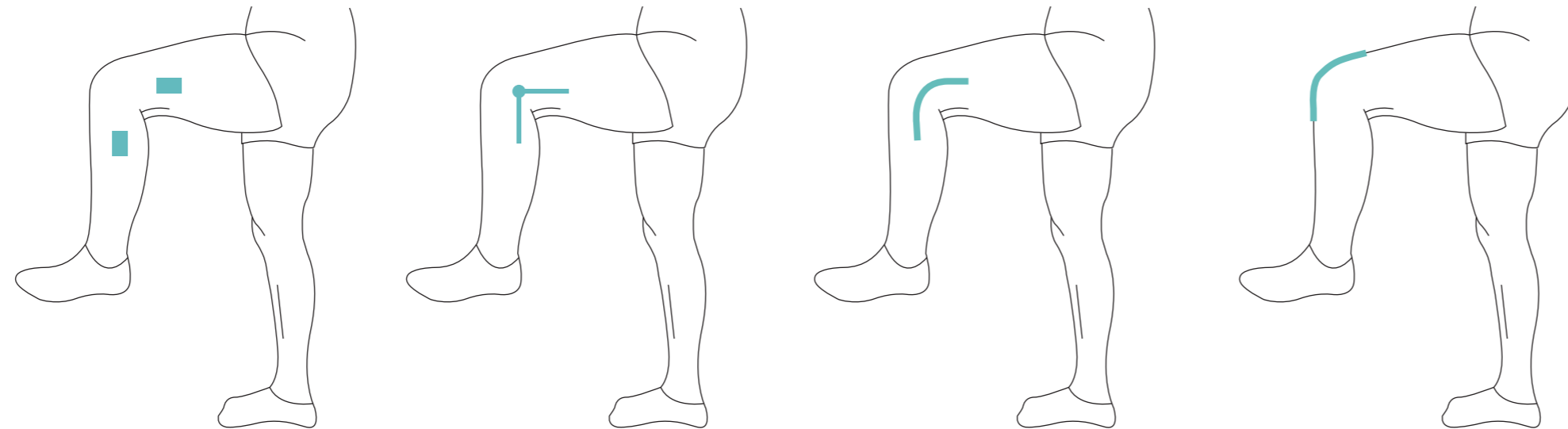


Figure 10. Four sensor types to monitor knee movement

However, they have limitations like durability, sensitivity to displacement, and pressure from clothing.

Compared to these sensors, textile-based stretch sensors can offer an innovative approach. The biggest advantage of textile strain sensors is their simplicity, high wearing comfort, flexibility, and subtle integration into clothing or wearables. Because the sensors are part of the textile itself, they fit to the body shape and do not restrict freedom of movement. This makes them suitable for long-term monitoring (Bozali et al., 2022)(Isaia et al., 2022) (Munro et al., 2007).

However, there are also challenges. The literature shows that textile sensors have not yet been tested enough under realistic conditions, like washing, sweating, long stress, and friction (Isaia et al., 2020) (Li et al., 2023) (Tang et al., 2022). Durability and wear of the conductive yarns have also barely been researched.

Furthermore, although many experiments have been conducted with these sensors, they have often remained prototypes that have not been developed and tested for use within the rehabilitation context. Despite these limitations, a combination of lightweight materials, flexibility, integration possibilities and low data processing complexity makes these sensors interesting for application in a knee sleeve. In such a system, they can give data on movement without reducing wearing comfort.

In addition, the production of textile sensors is well scalable. Industrially knitted structures with silver-coated yarns can give a linear and reproducible response up to about 40% stretch, with low hysteresis and stable performance for thousands of cycles (Bozali et al., 2022)(Li et al., 2023)(Shyr et al., 2014). It has also been demonstrated that stitched (sewn/embroidered) strain sensors also give reproducible responses across multiple sensor samples and repeated stretch cycles. Because these sensors can be made with commercially available conductive yarn and standard knit and sewing machines, they fit well into existing textile production processes. This makes them suitable for large-scale production (Alfaro & Trejos, 2023) (Jansen, 2020).

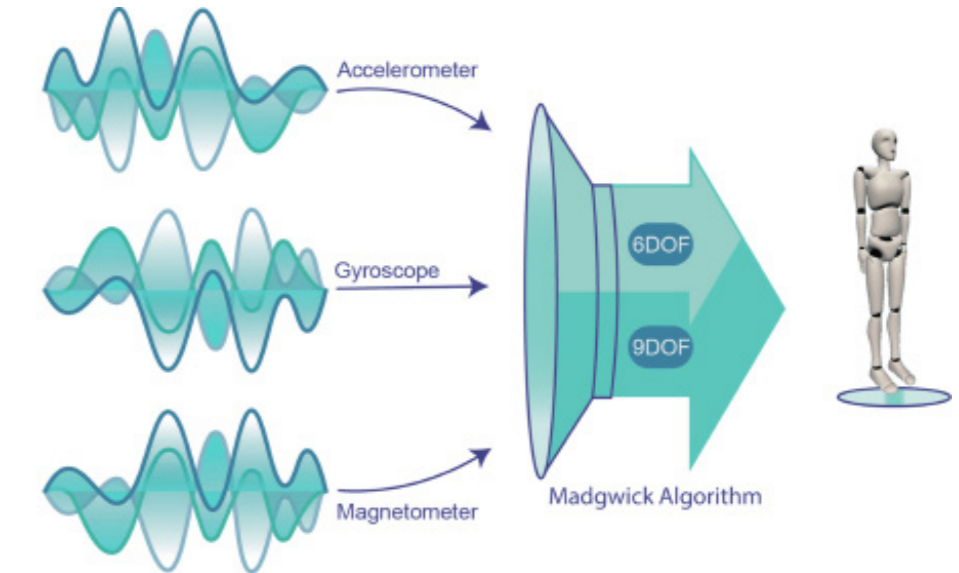


Figure 11. The operation of an inertial measurement unit (IMU)(QSense-Motion, 2026)

### 3.3 Opportunities and barriers

Literature research shows that textile strain sensors have both opportunities and limitations. To provide insight into these, the most important opportunities and barriers have been mapped out in the diagram on the right (figure 12). For each barrier is indicated how it will be included or addressed within the project.

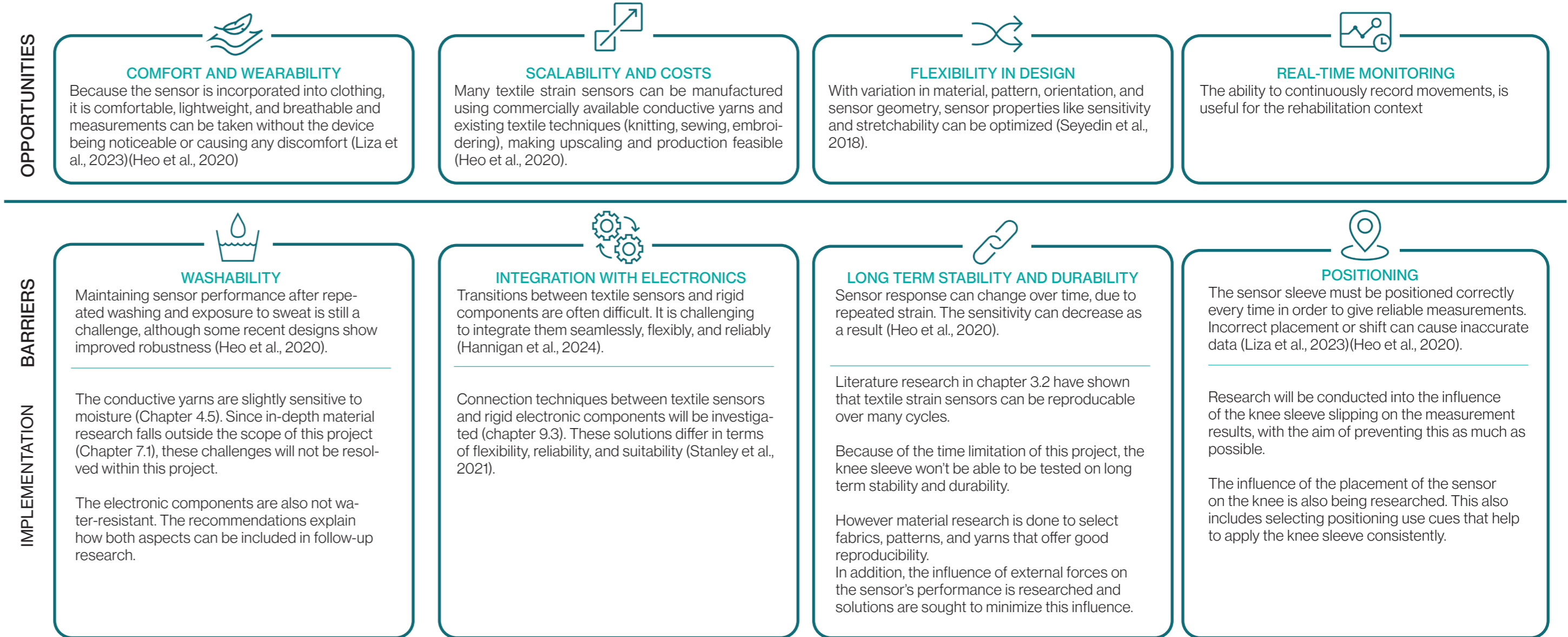


Figure 12. Opportunities and barriers of textile strain sensors and how the barriers are addressed



Figure 13 Knee brace(SunnyCamp, n.d.)

### 3.4 Knee braces

Various knee braces exist for different applications: to prevent injuries, to provide support during recovery or to stabilize (Elite Medical Supply of NY, n.d.).

Braces	Application	Functions
Prophylactic braces	Pre injury	Preventing injury during sports activities
Functional braces	Post injury	Stabilizing the knee during rotation and movement (after injury)
Rehabilitative knee braces	Post-surgery or injury	Restricting movement to protect injured ligaments
Unloader/Offloader knee braces	Treatment unicompartmental knee osteoarthritis.	Unloading pressure from one side of the knee joint to the other side

Table 1. Brace types including their application and functions

These braces each have a different composition of materials and structures, depending on the functions needed like support, protection, and flexibility. The choice of material and production method influences the functionality and comfort.

The sleeves and braces are often made of textiles, which are usually knitted spacer fabrics or elastic materials for comfort, breathability, and compression. By varying the yarn type and knit structure, the mechanical properties and comfort can be optimized (Yu et al., 2025)(Pereira et al., 2007). Braces often use a 1x1 rib stitch, Jacquard knit, single jersey, or combinations of different structures.

The use of spacer fabrics and perforated materials prevent production of sweat and overheating. In addition, a soft finish, soft edges, and ergonomic shapes reduce pressure points and skin irritation. For extra comfort and shock absorption, silicone or foam layers are sometimes added (Kim & Oh., 2023).

Knee braces are held in place as much as possible by compression fabric, silicone or rubber strips, additional velcro straps and fitting the anatomical shape (Kim et al., 2023).

### 3.5 Manufacturing methods

In this research part, the focus will be on two production methods: knitting (figure 14) and sewing/embroidering (figure 15). Other techniques, like weaving and braiding need stretchable conductive yarns, which is beyond the scope of the chosen technique. To determine which technique is most suitable for the knee sensor sleeve, both were investigated. The table below gives an overview of the advantages and disadvantages of both methods.

	Knitted sensor	Embroidered/sewed sensor
Method	The conductive yarn is integrated directly into the knitted fabric during the production process.	The conductive thread is embroidered/sewed onto the fabric.
Advantages	<p>The knitted structure allows the sensor to stretch and quickly return to its original shape.</p> <p>The three-dimensional knitting pattern enables a big change in resistance when stretched.</p> <p>The stitch density can be adjusted locally: tighter for compression around ligaments, looser in flexible zones.</p>	<p>The base material remains intact, which allows the fabric to retain its original structure and properties.</p> <p>There is a lot of freedom in the choice of base fabric, conductive threads, and embroidery patterns. Combination can optimally tailor the properties of the sensor.</p> <p>Embroidery and sewing can be done on existing clothing or textiles, which is useful for prototyping or integration into existing products.</p> <p>It is easier to replace or re-embroider without having to re-produce the textile.</p>
Disadvantages	It is difficult to adjust or repair the sensor patterns later, since it is integrated in the structure.	Embroidery lies on the fabric and is therefore exposed risk of snagging

Table 2. Two manufacturing methods including an explanation of their method and (dis)advantages

Figure 14. Knitting using a knitting machine



Figure 15. Sewing using a sewing machine(Violet, 2025)

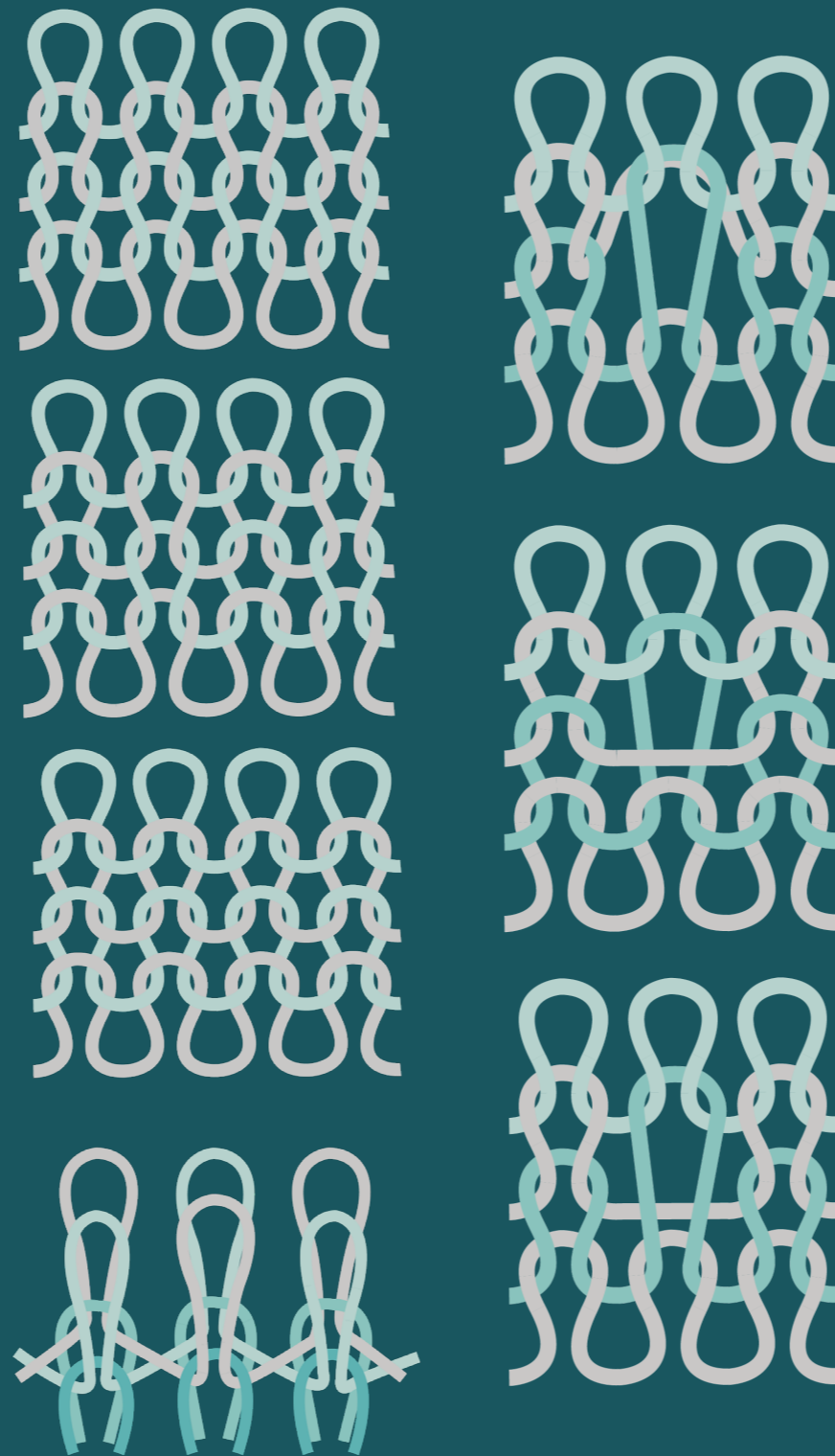
# Knitting

## Base patterns

Knitting has many different basic patterns. Within these patterns, there are various specific techniques that offer even more variety. These different patterns and combinations result in different properties like elasticity, thickness, and surface texture. The table below lists the possible base knitting patterns that are often used in strain sensors. They include a discription of their structure and characteristics.

Pattern	Description	Characteristics
Single Jersey (Tricot)	Single loop row, smooth on the front, ribbed on the back.	Low density, lowest GSM (grams per Square Meter), high stretch in transverse direction, thin, flexible.
Rib (1x1, mock)	Alternating knit and purl stitches.	Higher GSM than single jersey, more voluminous good stretch and recovery, thick.
Interlock	Two layers of single jersey knit, smooth on both sides.	High de nsity and GSM, thick, less stretch than rib, stable, less flexible than single jersey.
Purl	Backstitch (opposite of a knit stitch)	Soft, voluminous, stretchy in wale direction, textured on both sides.

Table 3. An overview of the base patterns, including a description and its characteristics (Assefa & Govindan, 2020) (Jansen, 2020)(Bozali et al., 2022)(Fischer et al., 2024)(Kejkar & Dhore, 2019) (Yan et al., 2020)



Pattern	Description	Characteristics
Tuck	Loops are held and created twice	More weight, thickness and porosity, higher elasticity, behavior depends on number/position of tuck, more volume and air, soft
Float	Threads run over (multiple) loop(s); no stitch	Increases GSM and thickness, Smoother, more closed back, Limited deformation, higher density and thickness
Miss	Loops are skipped; less dense	Less width stretch, Smoother, more closed back

Table 4. An overview of the specific patterns including a description and its characteristics (Amin et al., 2021) (Gorea et al., 2024)(Assefa Govindan, 2020) (Bukhonka, 2024)

Figure 16. Base patterns on the left (from top to bottom: Single jersey, Rib, Purl, Interlock) and specific patterns on the right (from top to bottom: Tuck, Float, Miss)

## Specific patterns

In addition, there are specific stitches that can be added within the basic pattern which can further influence the properties.

## Variables

Knitted sensors have various variables that influence their performance. The table below lists the variables investigated in various studies, along with the most optimal conditions.

Variable	Optimal condition (according to studies)
Knit density (NP value)	A higher NP (less dense knit), results in a greater working range and higher GF
Position conductive thread	Positioning inside results in a lower hysteresis and better linearity
Tuck-loop percentage	30% tuck loops result in an optimal balance between sensitivity, stretch, and comfort
Single vs. double sided	Double-sided results in more stable and a wider linear range

Figure 5. An overview of the variables within knitted sensors (Bozali et al., 2023) (Bozali et al., 2022) (Isaia et al., 2020) (Li et al., 2023)



Figure 17. A knitted sensor; the conductive yarn is integrated as a three-dimensional pattern in the knitted structure

## Embroidering/sewing

### Patterns

Within the embroidery/sewing technique there are different stitch patterns that result in varying properties like stretchability, sensitivity and linearity. The table below lists various stitch patterns collected from literature resources. The suitability is reviewed and the pattern is visualised.

Stitch type	Suitability	
Running stitch	Limited stretchability, only when using stretchable yarn.	
Coverstitch (top, bottom)	Bottom: Good elasticity and low hysteresis.	
Overlock stitch	Lower sensitivity but high transverse sensitivity. High stretchability	
Chain stitch	High sensitivity, linear behavior, low transverse sensitivity, and high stretchability.	
Zigzag	Possibility of double or even triple zigzag patterns on top of each other resulting in more contact points  Good working range, linearity, stretchability, repeatability, gauge factor, and low hysteresis Double zigzag; more stable in terms of working range and linearity but decreasing sensitivity	
Square wave	Works best with high stitch density but this can also reduce sensitivity or become noticeable on the fabric  Possibility of double or even triple square wave patterns on top of each other resulting more contact points  Great working range and higher sensitivity (two on top of each other works best because it improves linearity and stability, but can also reduce sensitivity or become noticeable on the fabric)	

Table 6. An overview of investigated stitch types, its suitability and its structure (Imran et al., 2024) (Tangsirinaruenart & Stylios, 2019) (Martínez-Estrada et al., 2021) (Jansen, 2020) (Dupler & Dunne, 2019)



## Embroidering/sewing

### Variables

Embroidered/sewed sensors (Figure 18) have various variables that influence their performance. The table below lists the variables investigated in various studies, along with the most optimal conditions.

Variable	Optimal condition (according to studies)
Stitch type	Patterns with good contact points (e.g., zigzag) higher sensitivity and linearity.
Stitch density	Average density balance between stability and sensitivity.
Row spacing	Optimal density (not too dense, not too loose) good conductivity without short circuits.
Stitch length	Shorter stitches result in higher sensitivity, but creates risk of hysteresis.
Orientation of stitches	Alignment towards stretch improves linearity and elasticity.
Type yarn	Silver-coated yarns have conductivity and a low base resistance.

Table 7. Variables investigated in various studies including its optimal condition (Martinez-Estrada et al., 2021)(Alfaro & Trejos., 2023)(Jansen, 2020)

Figure 18. A stitched sensor; the yarn is stitched as a zigzag structure onto the base fabric

## Chosen method

Both knitting and embroidery/sewing offer many advantages in the development of textile sensors, but looking at effectively integrating a sensor into a knee wearable, the flexibility and control of embroidery/sewing techniques play a decisive role. These techniques offer more options for carefully selecting the base material, ensuring both optimal sensor performance and comfort for the user. In addition, the sensor pattern can be precisely optimized to maximize variables like sensitivity and repeatability and ensure smooth integration into the wearable.

For knitting, the possibilities are more limited: the fabric structure and available possible patterns allow less freedom in combining comfort, fit, and sensor sensitivity.

Therefore, this project has chosen to continue with embroidery/sewing as the manufacturing technique for the textile strain sensor, enabling optimal use of the practical advantages for integration into a knee wearable.



Figure 19. The production of a sensor sample

## 3.6 Data processing

Wearables like Fitbit, Apple Watch, and Garmin Vivoactive are designed to continuously record, process, and present movement data to the user. Although the process varies a bit for each brand, most commercial wearables follow a similar data process from sensor measurements to visualizations in an mobile app.

To gain insight into how movement data is processed in existing sports wearables, the general data processing method was investigated. This provides a frame of reference that can help to tailor the data processing of the sensor sleeve system to this method as closely as possible, or at least to understand how this should be addressed at a later stage.

### 1. Sensory data collection

The process starts with the sensor(s) in the device, like an accelerometer, gyroscope, or heart rate sensor (figure 20, 1). These sensors measure physical parameters like acceleration and heart rate. The raw signals are received via a microcontroller that reads them continuously or in cycles

(Tipparaju et al., 2021)(Dobrescu et al., 2024). This often happens in low sampling frequencies or duty-cycles: the sensor measures at short intervals. The microcontroller averages or filters the raw samples into “features”. This minimizes energy consumption and limits the amount of data that needs to be send (Choi et al., 2025)(Jan et al., 2023).

### 2. Local storage and buffering

Because wearables are not always connected to the internet, the measured data is temporarily stored in internal memory (figure 20, 1). The data is send when a connection is re-established with an external device like a smartphone or computer. This local storage is important for offline data collection (Choi et al., 2025)(Jan et al., 2023).

### 3. Wireless transfer to a gateway (BLE synchronization)

Communication between the wearable and the phone takes place via Bluetooth Low Energy (BLE) (figure 20, 2). The wearable acts as peripheral transmitting data packets, while the smartphone acts as the central/host that receives this data (figure 20, 3). Hosts have more computing power and

can perform additional preprocessing/analysis before sending the data to the cloud (figure 20 5, 4)(Tipparaju et al., 2021)(Muzny et al., 2019)(Temple et al., 2023).

### 4. Upload to the cloud

As soon as there is internet access, the app uploads the data to the cloud (figure 20, 4), where long-term storage and analytics take place. Algorithms in the cloud are used to detect stress, sleep, sickness etc (figure 20, 5) (Witt et al., 2019) (Temple et al., 2023).

### 5. Visualization in the app

Once the data has been analyzed, it is sent back to the mobile app (figure 20, 6). Here, the results are visualized in graphs, daily overviews, or trends. The app retrieves the relevant data from the cloud via a secure API (Application Programming Interface) and displays it in an understandable form (De Arriba-Pérez et al., 2016)(Angelides et al., 2018).

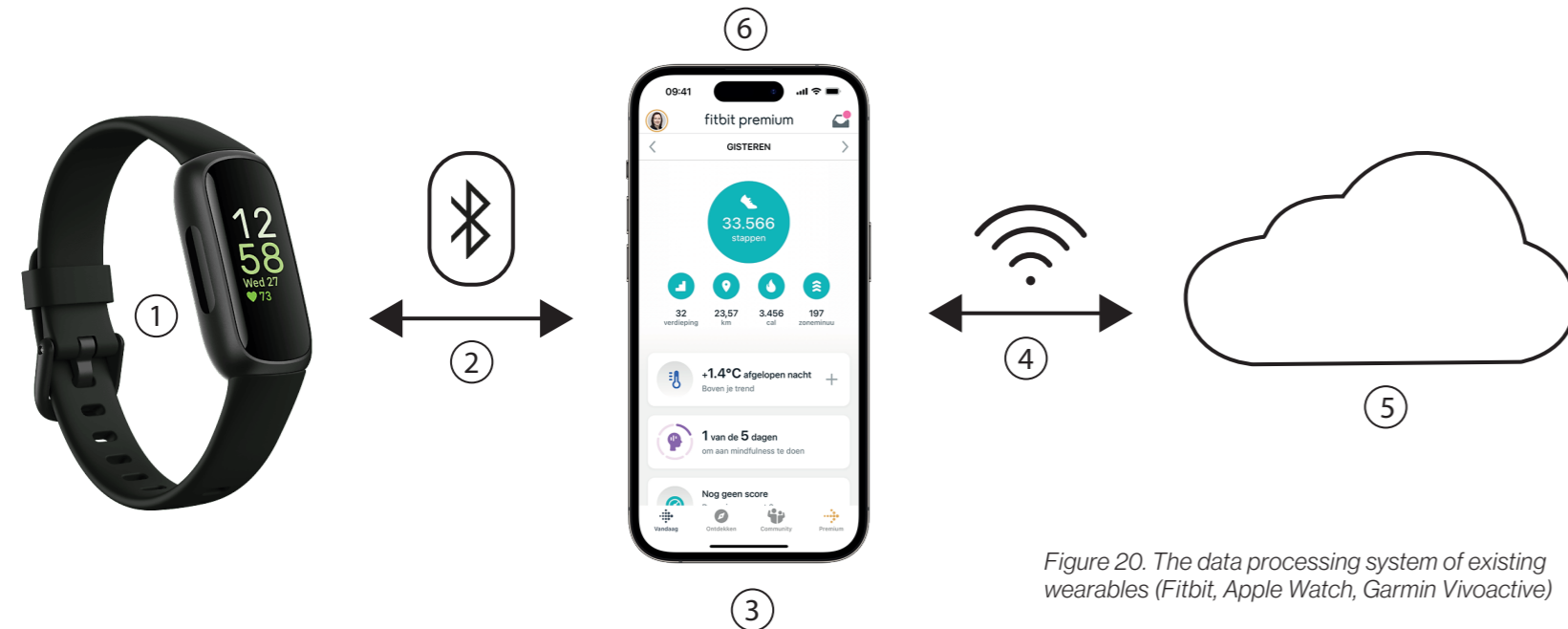


Figure 20. The data processing system of existing wearables (Fitbit, Apple Watch, Garmin Vivoactive)

## Knee sleeve data processing

Because of time constraints, the data processing of the knee sensor sleeve will not fully correspond to that of existing commercial wearables. However, the aim is to achieve an implementation that approximates the final working method as closely as possible.

Python Streamlit will be used to realize this data processing for the user test. This platform makes it possible to develop a website using python that can receive Bluetooth Low Energy (BLE) sensor data transmitted by the Seeeduino XIAO microcontroller, display it in the streamlit environment, and then store it in a Google Sheets (Figure 21).

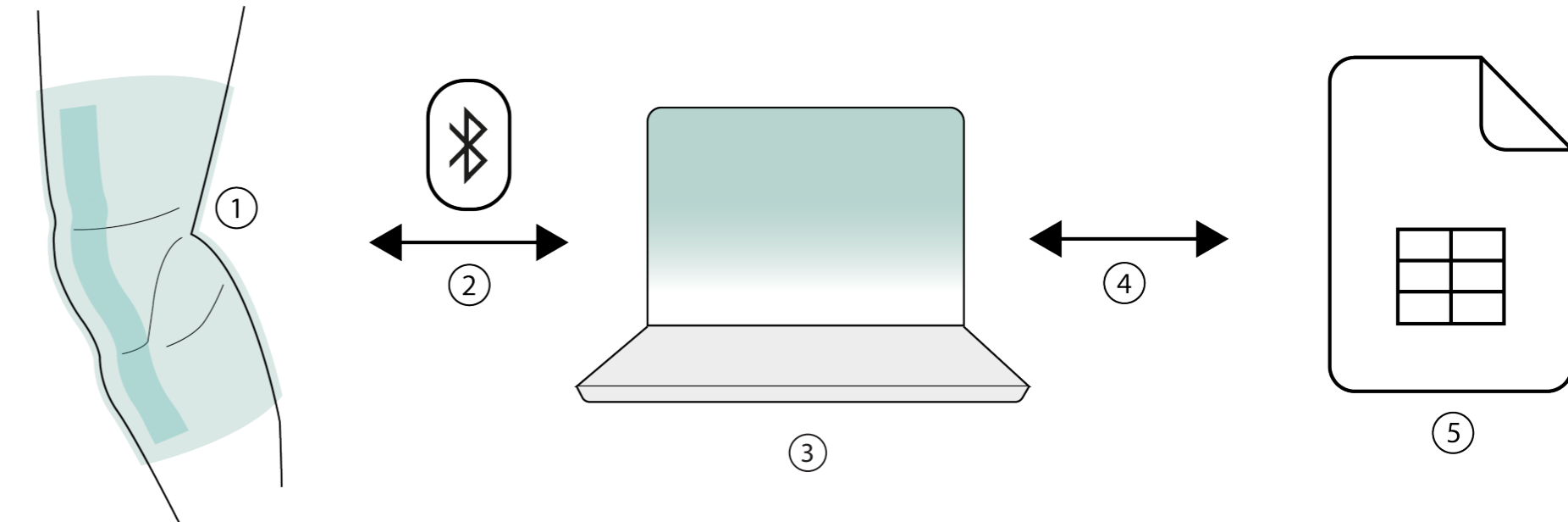


Figure 21. The data processing system of the knee sleeve

# TAKEAWAYS & IMPLEMENTATION

## Key takeaways

Knee flexion is the most important and relevant movement for rehabilitation, as it is directly linked to recovery, comfort, and functional daily use.

Textile strain sensors are a promising alternative to IMUs, flex sensors, and potentiometers because they are comfortable, flexible, unobtrusive, and well scalable.

The biggest challenges are washability, durability, sensitivity to displacement, and reliable integration with electronics.

Existing knee braces show that the right choice of materials, knitting structures, and anatomical shapes are important for comfort and for preventing slippage.

Knitting and embroidery are suitable production methods: they offer a lot of design freedom and can accurately integrate conductive yarns into stretchable structures.

Wearable systems often process data via a fixed flow: local registration --> buffering --> BLE transfer via phone --> cloud analysis --> user-friendly visualization.

## Implementation

The focus will be on knee flexion because this movement is not only clinically the most valuable, but also the most suitable for strain measurement.

The focus will be on textile strain sensors, because accesability, comfort and wearability, the biggest advantages of strain sensors, are important factors for long-term use of a knee sensor sleeve.

These challenges will be addressed as much as possible within the time scope of this project. The Scope chapter discusses what will and will not be included.

The design of the knee sleeve will incorporate and test insights from existing braces: stretchable compression fabric, antishift methods, and ergonomic shapes to increase stability and comfort.

The focus will be on the sewing/embroidery production technique because the flexibility and control of this technique offers valuable advantages for the development of the knee sensor sleeve.

This data structure provides an overview of how the data can best be processed in practice. The structure will be implement as far as possible within the time constraints (see KinetiK Data Processing).





Figure 22. A variety of samples were tested during the experimental research

## 4. Experimental research

This chapter describes the selection of sensor components, including fabric, yarn type, and pattern, based on experimental testing.

- 4.1 Testing setup and goal
- 4.2 Fabrics
- 4.3 Patterns
- 4.4 Conductive yarn types
- 4.5 The influence of water
- 4.6 Chosen sensor properties
- 4.7 Discussion and conclusion

### 4.1 Testing setup and goal

#### Goal and research questions

The goal of this test is to select various elements to create the most optimal sensor.

The tests are used to answer the following research questions:

- Which fabric transfers mechanical strain to the sensor most gradually and effectively, offers a sufficiently large work range, gives sufficient rebound to limit hysteresis, and enables repeatable use of the sensor?
- Which yarn pattern results in the biggest and most linear change in the number of electrical contact points when stretched, and thus in the largest and most stable resistance change?
- Which yarn type delivers the best sensor performance in terms of sensitivity (gauge factor), linearity, repeatability, and minimal hysteresis?

#### Testing setup

A LETT meter with resistance measurement was used to determine the performance of the textile strain sensors (Figure 23). During the measurements, a sensor sample was slowly stretched using mechanical clamps (green), while the electrical resistance was measured using separate clamps (red).

To ensure consistent measurements and reliable comparison between the different samples, a fixed initial length of 10 cm and a maximum extension of 35% were used for all tests. The samples were stretched at a constant speed of 50 mm/min for three stretching cycles. This loading allowed for analysis of changes in resistance and thus assessment of the sensor performance.

The obtained measurement data forms the base for comparing and selecting the most suitable combination of fabric, yarn pattern, and yarn type for the development of an optimal textile strain sensor.

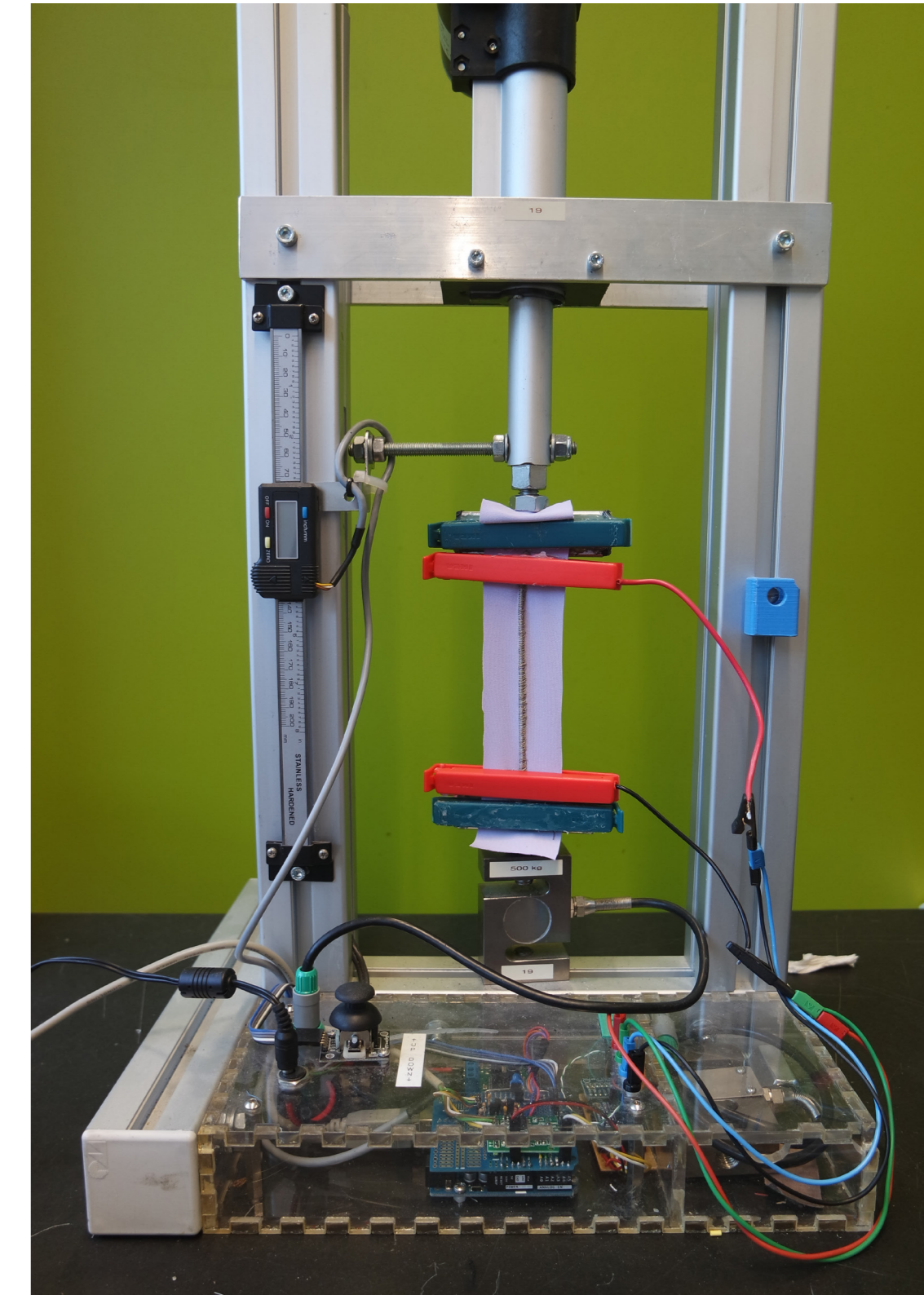


Figure 23. The LETT meter with resistance measurement that was used throughout the project for the sensor research tests

## The variables

The quality of the performance of the sensors was assessed based on multiple variables. Figure 26 shows an example of the resulting graph of a sensor sample stretched by the LETT meter, showing how the quality of the variables can be evaluated by the graphs lines.

### Work range

The sensor must have a working range that exceeds the relevant range of motion of the knee, namely 0–130° till a maximum of 150° (Kono et al., 2018). A working range that is too small causes the sensor to reach its maximum response too quickly. This results in a premature plateau and loss of usable signals. A sufficiently large working range ensures that the sensor output remains within a usable, linear range throughout the entire movement.

### Gauge factor (GF)

The gauge factor is a measure of the sensitivity. It indicates how much the resistance changes in relation to the strain; the slope.

A higher GF means that the sensor is more sensitive to strain, which gives more accurate responses.

To be able to accurately measure change in strain, the gauge factor should be at least 1. This means that for every 10% stretch the resistance also increases with 10% (Jansen, 2020).

$$GF = \frac{\Delta R / R_0}{\varepsilon}$$

$\Delta R$  = change in resistance  
 $R_0$  = initial resistance  
 $\varepsilon$  = applied strain

### Linearity

A second important aspect is smooth and reproducible change, i.e., a good linearity. Linearity indicates the extent to which the sensor shows a linear relationship between the strain and the measured resistance. Ideally, the measurement signal follows a straight line and the resistance changes progressively with increasing stretch, rather than abruptly jumping. The sensor

must have a smooth, linear response that enables repeatable measurements and maintains the signal reliably within the range of motion. Linearity is often expressed as the maximum deviation from an ideal straight line and given in  $R^2$ . The closer  $R^2$  is to 1, the more linear the response (Tangsirinaruenart & Stylios, 2019).

### Hysteresis

Hysteresis describes the difference in sensor output between increasing and decreasing strain and should ideally be as low as possible. It indicates whether the sensor “lags behind” in its response. Upon release of the stretch, the resistance should return almost completely to its original resistance. Hysteresis can be expressed in extension or in resistance (Jansen, 2020).

$$H_\varepsilon = \frac{\Delta \varepsilon_{\text{hys}}}{\varepsilon_{\text{max}} - \varepsilon_{\text{min}}}$$

$\Delta R_{\text{hys}}$  = difference in resistance between the loading and unloading curves at the same strain

$$H_R = \frac{\Delta R_{\text{hys}}}{R_{\text{max}} - R_{\text{min}}}$$

$\Delta \varepsilon_{\text{hys}}$  = difference in strain between the loading and unloading curves at the same resistance  
 $\varepsilon_{\text{max}}, \varepsilon_{\text{min}}$  = maximum and minimum strain  
 $R_{\text{max}}, R_{\text{min}}$  = maximum and minimum resistance

### Repeatability

Repeatability indicates how consistently the sensor measures the same strain values in repeated cycles under the same conditions. A sensor that shows deviating values after just a few movements is not usable. Mechanical deformation must occur consistently at the same locations.

Repeatability is evaluated by analyzing drift, which describes the gradual change in sensor output over repeated stretching cycles. Low drift indicates that the sensor response stays stable over time, indicating good long-term

$$\text{Repeatability (\%)} = \frac{\sigma}{\mu} \times 100$$

$\sigma$  = standard deviation  
 $\mu$  = average value

repeatability. Although repeatability/drift has no standard formula, one way to calculate the repeatability of a textile strain sensor is to take the standard deviation of the sensor output over repeated measurements at the same strain value (Cdsentec, 2022).

### Acceptable values for sensor selection

Literature does not explicitly specify minimum limit values because sensor requirements depend on the intended application and measurement conditions. Therefore, minimum/maximum values were chosen for this project based on the functional requirements of a knee sleeve for rehabilitation; the goal is not high precision, but the ability to reliably monitor changes in knee movement.

The table below shows the minimum/maximum values that will be pursued to create a usable sensor for sensor sleeve within rehabilitation.

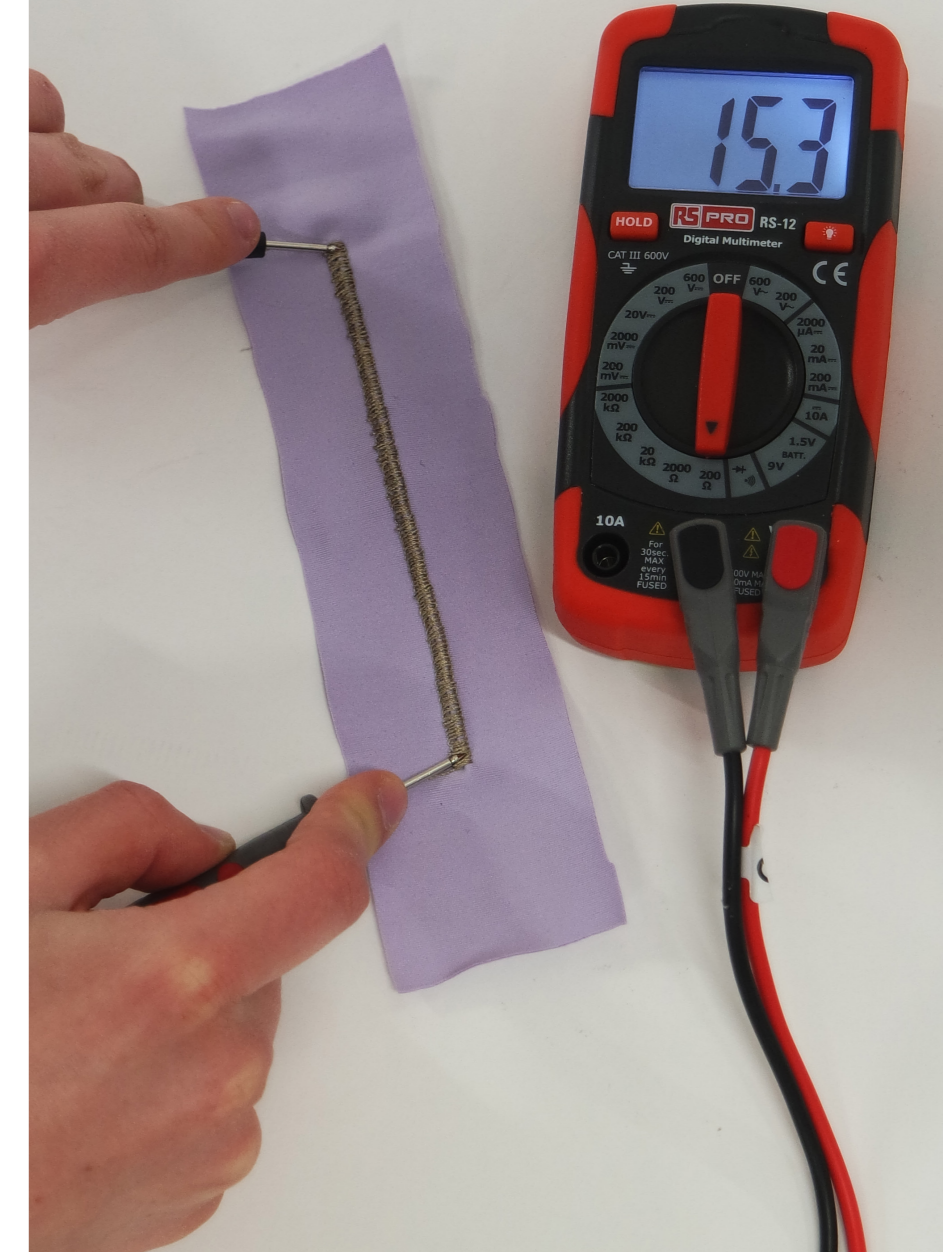
In this case, hysteresis for example is less important than repeatability, since it is important that repeated movements produce the same sensor values, whereas the difference between bending and extending does not affect the measured angle and is therefore less relevant.

Variable	Value
Work range	$\geq 35\%^*$
Gauge factor	$\geq 1$
Linearity	$\geq 95\%$
Hysteresis	$\leq 20\%$
Repeatability	$\leq 1\%$

Table 6. The minimum/maximum values that will be pursued

\* The chosen working range of 35% was based on a calculated elongation of fabric on knee, which later turned out to be incorrect. The actual elongation is approximately 50% and is discussed in chapter 13 Validation evaluation. However, an elongation of 35% was used for the tests of the sensors. Although the actual working range is larger, the used 35% elongation is sufficient to compare the sensors and to assess their performance.

Figure 24. A multimeter was used to measure resistance of the sensor at varying distances at rest.



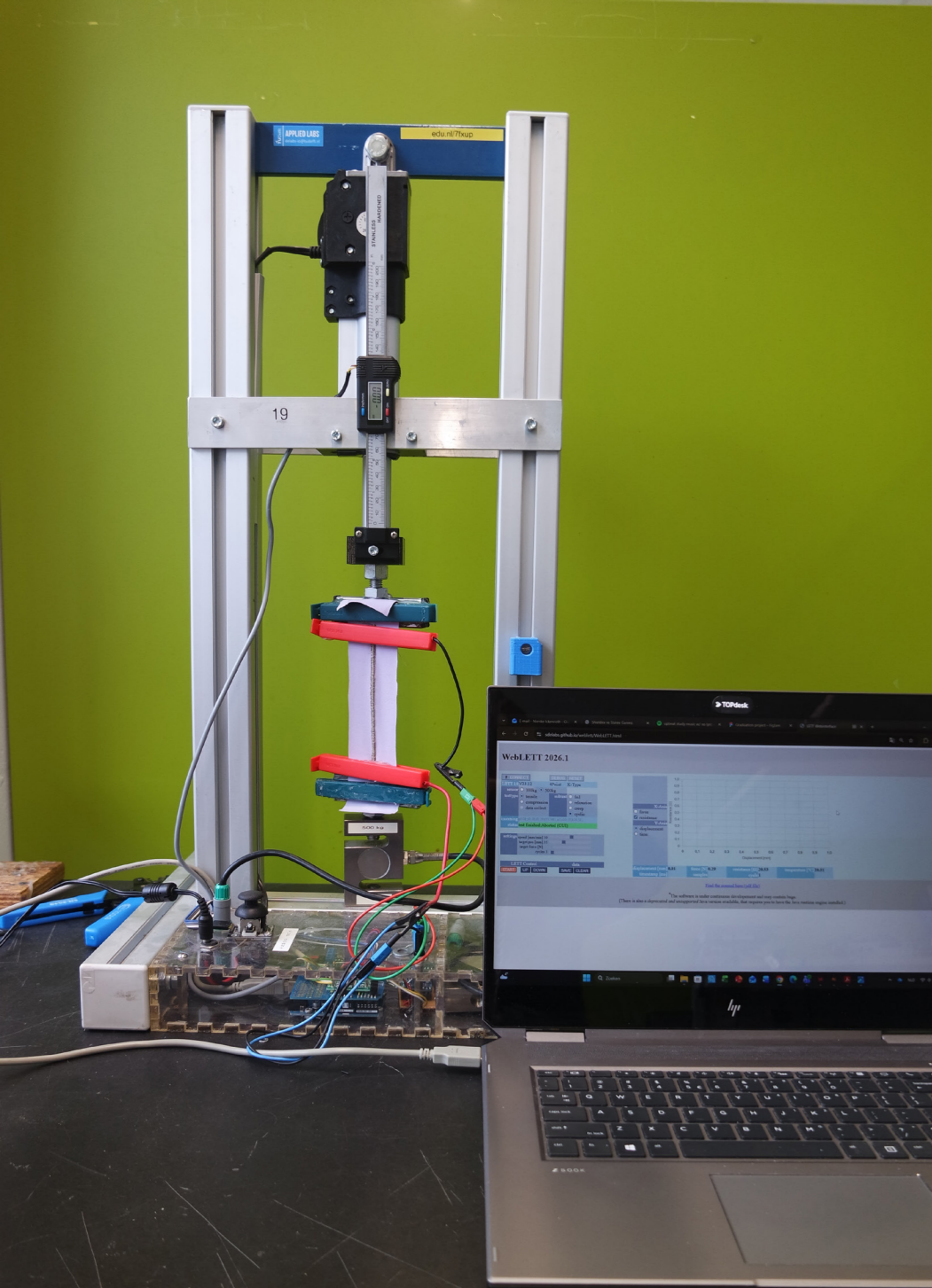


Figure 25. A multimeter was used to measure resistance of the sensor at varying distances at rest.

The graph in figure 26 shows the resistance plotted against the extension of a sensor over 8 subsequent stretching cycles. The lines during stretching (upper lines) show slightly higher resistance values than during the return movement, which is because of the hysteresis effects discussed earlier. The small deviations at the beginning and end of the curves (at 1% and 31% stretch) are probably the result of relaxation effects: when the sensor is held at constant stretch for a short time during the reversal of the direction of movement, the sensor fibers rearrange themselves slightly.

Despite these effects, the lines during stretching and return are close together, which means that the sensor gives a similar response each cycle. This indicates that the measurements are reproducible and that the behavior of the sensor is consistent over multiple cycles.

Gauge factor	Linearity	Hysteresis	Repeatability
2,27	0,96	16.31%	0.59%

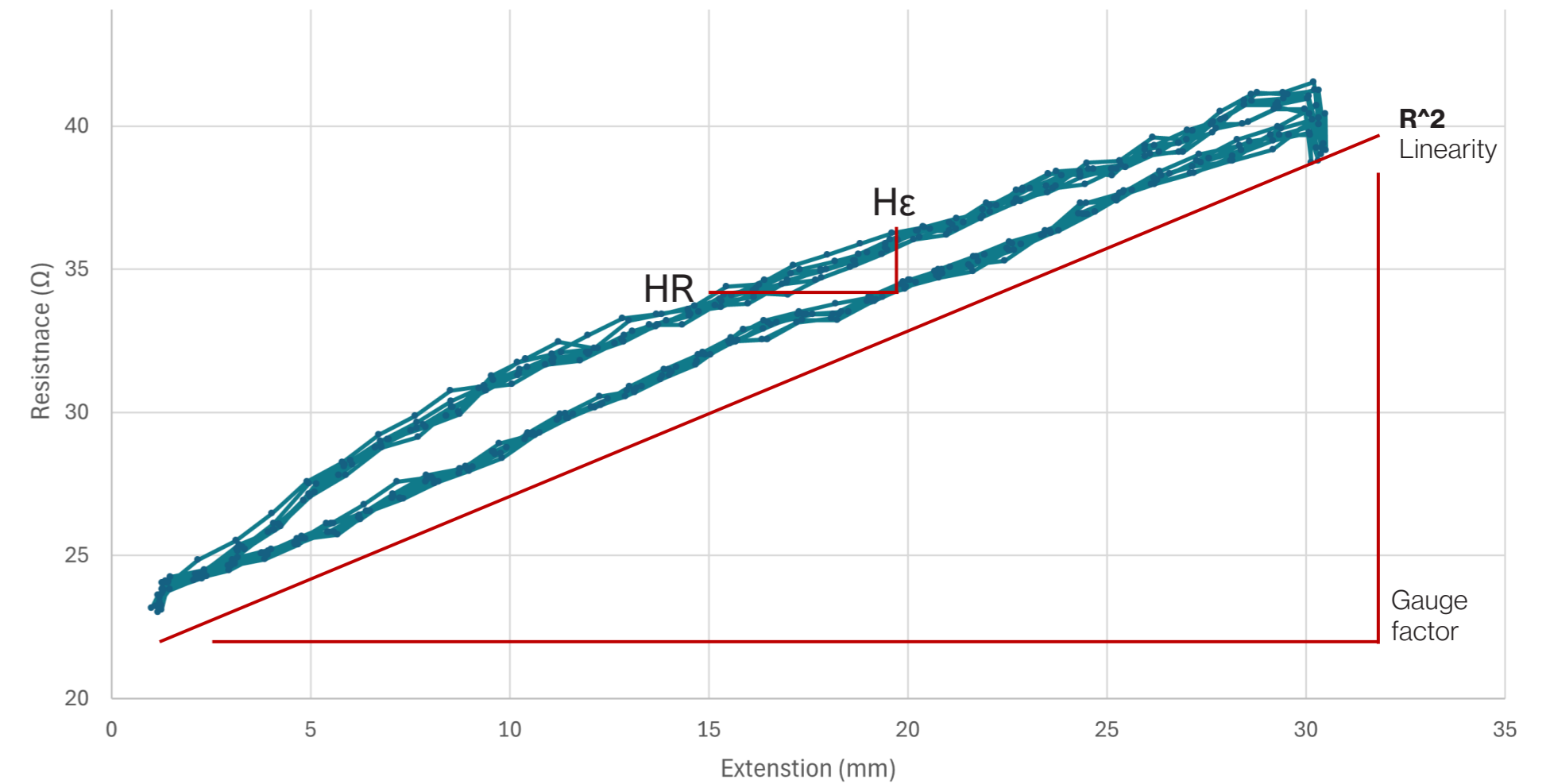


Figure 26. A graph with resistance versus extension of a sensor showing good sensitivity, linearity, repeatability and present hysteresis

## 4.2 Fabrics

The choice of textile has a big impact on both the electrical and mechanical performance of the strain sensor. The materials investigated varied in thickness, stretchability, and material composition.

The goal of this research was to investigate the influence of different textile types on the performance of a textile strain sensor.

The sensors were made with different base materials, each with a fixed zig-zag pattern (5 mm width, 0.5 mm density) and the same yarn type (SHIELD-EX® Yarn 235 f 36 dtex 2PLY HC+ B). The sensors are shown on the right including microscope images of their structure and sensor, their stretchability (expressed in Newton; the amount of force required to stretch the sensor 35%) and thickness and a performance graph (Figure 27).

### Thickness of the Fabric

The thickness of the fabric appears to need a balance between mechanical support and strain transfer:

**Too Thick:** While a thicker fabric, like a spacer fabric, can transfer strain well and keep the yarn stable, a fabric that is too thick can lead to higher forces needed to stretch. This can cause unwanted shifting or deformation, for example, in applications on knees. The yarn is more difficult to stretch consistently, making the resistance increase less linear.

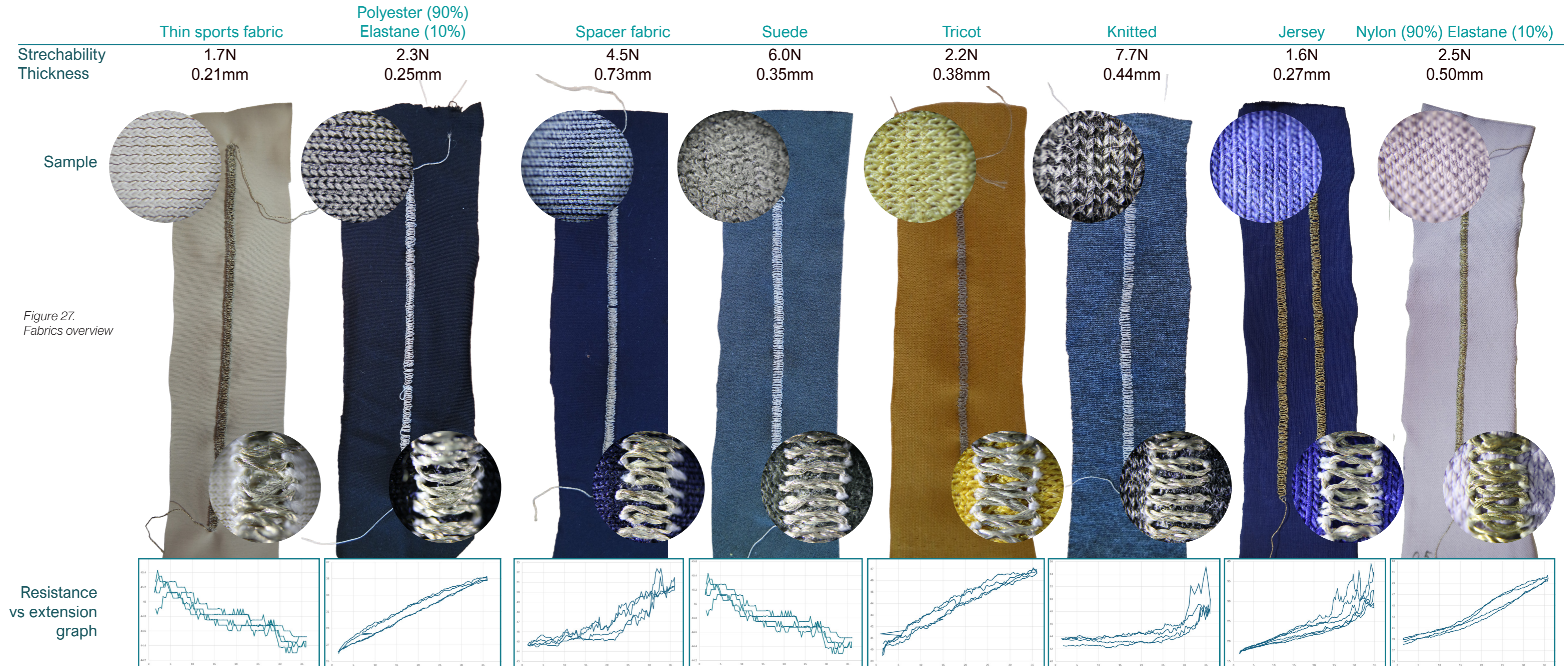
**Too thin:** Thin fabrics like the thin beige sports fabric appear to transfer stretch less effectively to the conductive yarn. This seems due to the quite stiff zigzag structure of the yarn. In thin, highly stretchable textiles, this creates a mismatch in stretchability, causing variable resistance and a nonlinear response.

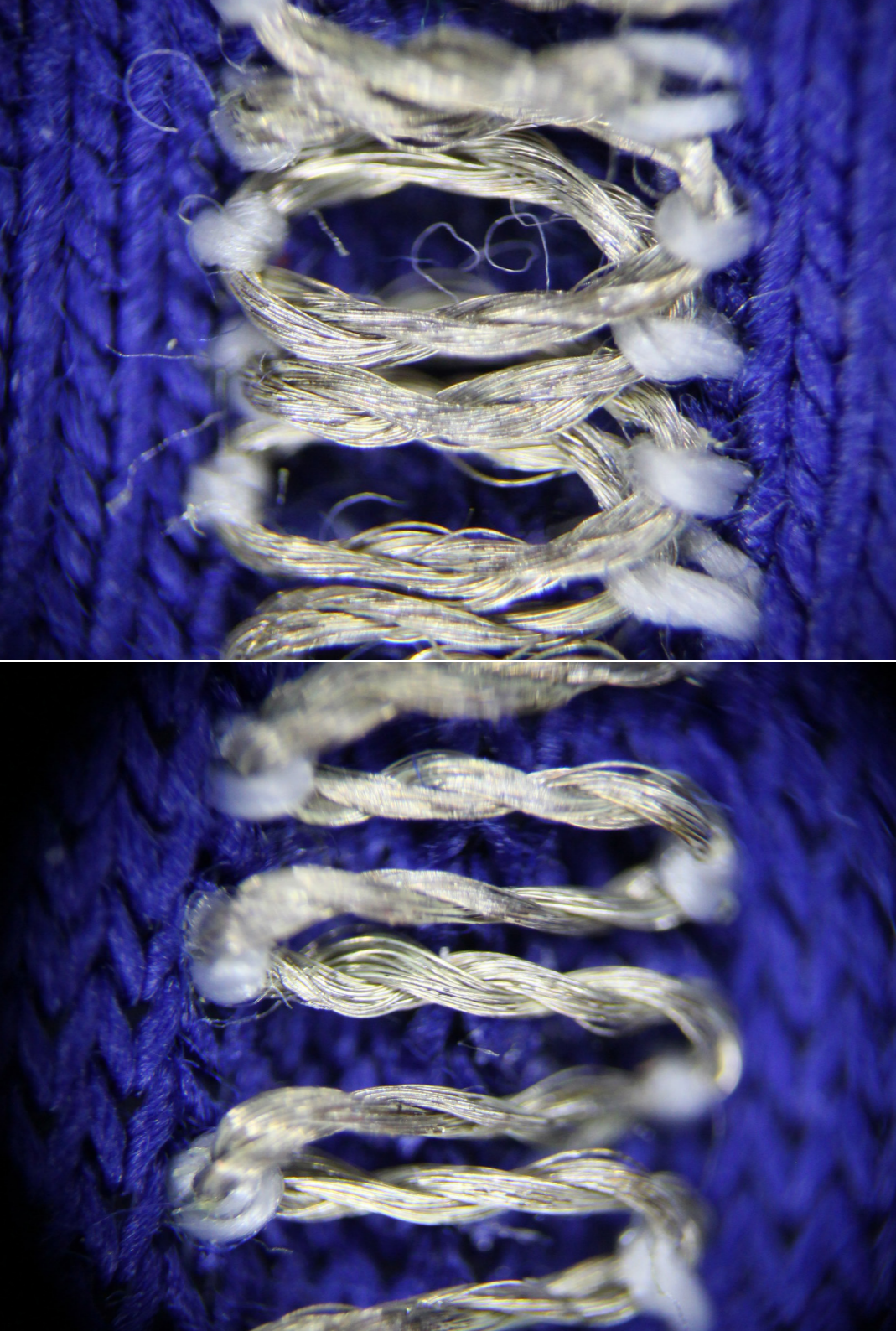
### Stretchability of the Fabric

The stretchability of the textile must be carefully adjusted:

**Too low stretchability:** The yarn is not stretched sufficiently, and the resistance hardly changes. This leads to limited sensitivity and a low Gauge factor, like was observed with the green suede fabric for example.

**Too much stretchability:** In very stretchable fabrics, the stretch is not transferred consistently to the yarn, as with the beige sportswear fabric. This results in a variable and often nonlinear response.





A medium-stretch tricot fabric, like the yellow tricot seems to offer a good balance. The stretch and rebound mechanism is quite linear, allowing the sensor to show predictable changes in resistance, even though the gauge factor remains relatively limited.

#### Combination of Material and Composition

The material composition of the textile plays an important role: Polyester or nylon combined with elastane (like the black and purple nylon-elastane fabric) creates a fabric that offers both enough stretch and a strong rebound. This combination ensures that the conductive yarn is stretched evenly and in a controlled way, which results in both a linear response and a high gauge factor. The optimal balance between thickness and elastane percentage in the nylon/polyester-elastane fabric explains why this fabric gave the best performance in terms of sensitivity and reproducibility.

#### Conclusion

A textile that is thick enough to keep the yarn stable, offers average stretchability, and has a composition of polyester/nylon and elastane produces the most predictable and sensitive textile stretch sensor. The nylon-elastane fabrics from the experiments met these criteria and showed the highest linear response and gauge factor, making it the most suitable.

#### Additional Insights from Water Contact

Initially, a washable paper layer was stuck to the fabric to prevent stretching during sewing. After sewing, the layer was removed by dissolving it in water. However, this negatively impacted the sensor's performance: the resistance became very variable and the  $\Delta R$  reduced. Therefore, it was later decided to no longer use a paper layer. Although this may cause the fabric to bulge slightly at the yarn location, it has no noticeable negative impact on linearity or resistance change.

The influence of water will be analyzed later in this chapter.

Figure 28. This figure shows how the silver-coated yarns form a zigzag structure. These are held in position by the white stitch yarns coming from the bobbin. In rest position, the conductive yarns touch each other at various points, resulting in low resistance (upper image). When stretched, these contacts gradually break, causing the resistance to increase (lower image).

## 4.3 Patterns

Besides the fabric type, the design of the stitching pattern also plays an important role in the performance of textile strain sensors. The patterns used were variations of zigzag stitching with varying stitch distance, as the zigzag pattern in general showed the most favorable results in the literature (Figure 29)(Alfaro & Trejos, 2023)(Jansen, 2020)(Imran et al., 2024).

#### Influence of stitch distance

The stitch distance determines the density of the conductive path, which affects both linearity and sensitivity (Martínez-Estrada et al., 2021). A distance of 0.5 mm creates more contact points between the yarn and the fabric, resulting in a bigger change in resistance. This increases sensitivity to small differences in stretch, which is valuable when maximum sensitivity is desired. At the same time, the higher density seems to make the pattern more sensitive to sewing tolerances: small differences in yarn tension or position cause local variations in stretch, reducing linearity and increasing hysteresis. A stitch density below 0.5 mm caused production problems due to the pattern's thickness.

A 0.8 mm stitch pitch provides a more linear response with lower hysteresis, although the  $\Delta R$  is smaller. The yarn is less tightly integrated, resulting in a more even stretch distribution and less sensitive to small deviations during the sewing process. At the same time, a too big distance will lead to too few contact points, making the sensor less sensitive and resulting in smaller resistance changes.

#### Influence of Pattern Shape

The shape of the zigzag pattern also influences the sensor response. A single zigzag pattern offers the most direct relationship between strain and resistance and is generally the most linear. The pattern is easy to control and does not require perfect alignment, ensuring reliable response.

A double zigzag pattern can theoretically increase sensitivity by doubling the total conductive length. In practice, however, the linearity proved to be worse: positional differences between the two layers seemed to lead to uneven strain distribution.

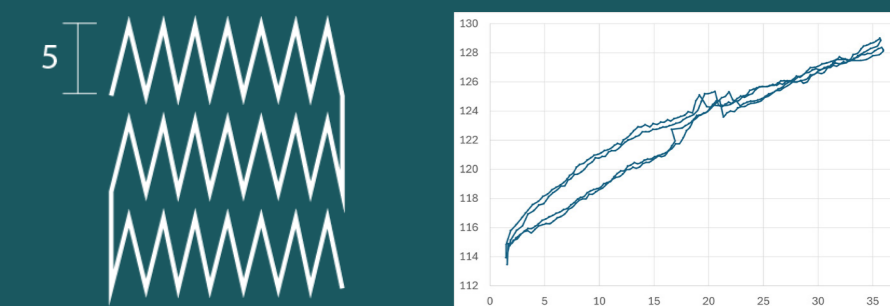
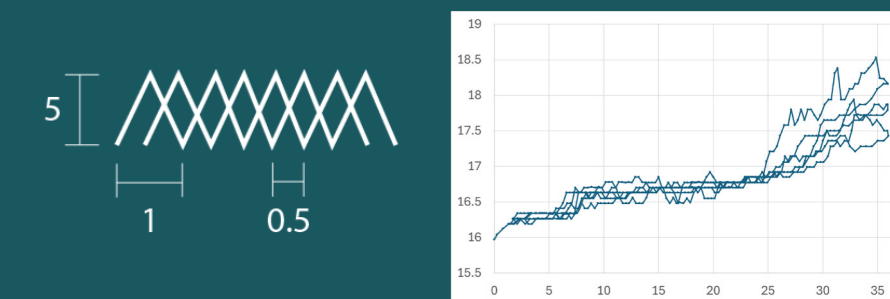
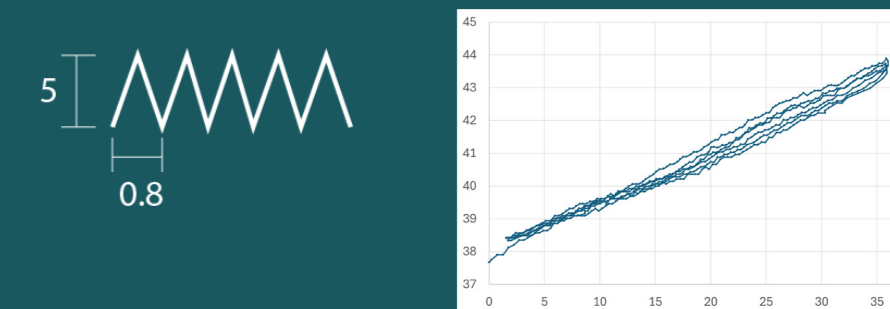
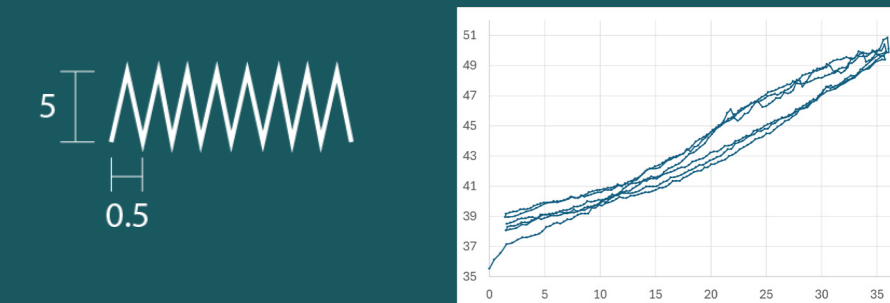


Figure 29. Four patterns including their sensor response explained by a resistance ( $\Omega$ ) vs extension (%) graph

### Multiple rows

The bottom graph shows the response of three sensor rows. This shows that it exhibits more hysteresis than a single row, possibly because of the cumulative hysteresis effects of each row. In addition, additional rows increase the resistance change, but add little value because they register the same signal without increasing measurement accuracy.

### Conclusion

Based on the experiments, a single zigzag pattern with a density of 0.8 mm provides the optimal combination. Although the  $\Delta R$  is smaller than with 0.5 mm, this pattern delivers a more linear and reproducible response, important for reliable sensor performance.

## 4.4 Conductive yarn types

### Analysis

To investigate the influence of yarn properties on the performance of strain sensors, various conductive yarns were tested. Because many previous studies have shown that silver yarn generally performs well (e.g. (Tangsirinaruenart & Stylios, 2019) (Martínez-Estrada et al., 2021)), the focus is on various silver-coated yarns. The tested yarns vary in thickness, number of filaments, and construction.

Four yarns were selected based on their potential for use in a textile strain sensor and their variety of properties. These were tested using the yellow tricot fabric.

More information about the tested yarns can be found in the overview on the right. Table 6 explains the meaning of the terms in the names of the yarns.

<b>(D)Tex</b>	A unit of measurement for the thickness or mass of yarn. The higher the (D)Tex number, the thicker the yarn.
<b>f</b>	A unit of measurement for the number of filaments. The more filaments, the better the conductivity.
<b>PLY</b>	A unit of measurement for the number of strands. The more strands (ply), the thicker the yarn and the lower the resistance per unit length.

Table 6. Yarn name specifications explanation

The yarn **SHIELDEX® 235 f 36 dtex Z130 (1)** exhibited a relatively high base resistance of  $\pm 500 \Omega$ , but only a small change when stretched, resulting in a GF of 0.14. This indicates very low sensitivity. The measurement lines are somewhat linear but noise of approximately 10 ohms is observed at the start of stretching (0–5 mm). In addition, the cycles are slightly separated, indicating limited reproducibility.

The **Silver-Tech 120 Tex 28 (2)** variant had a higher starting resistance of  $\pm 875 \Omega$  with a GF of 0.74. This makes the yarn more sensitive than Silver-Tech, but still not sufficient. The linearity of the response is slightly better than Silver-Tech.

The **SHIELDEX® Yarn 235 f 36 dtex 2PLY HC+ B (3)** has a low base resistance of  $\pm 35 \Omega$ . The 2PLY construction with two coated strands seem to increase conductivity and mechanical strength, thus improving sensitivity showing a GF of 1,22. The yarn's thickness and stiffness appear to maintain a stable contact network, causing the structure to change uniformly with stretch and keeping the measurements fairly consistent. However, reproducibility remains limited. In addition, the graph indicates that the response begins to level off at 25% strain which means it seems to have a limited working range.

Another tested yarn was labeled with Silver yarn Dtex 604 on the spool, giving limited specifications (bottom yarn type, figure 30). However the graph shows a slightly lower base resistance of  $\pm 31 \Omega$ , a higher GF of 1,43 and a better linearity, this yarn seems to be the same as the SHIELDEX® Yarn 235 f 36 dtex 2PLY HC+ B. The resistance per meter of the two yarns are the same, the microscopic pictures show similar construction and the graphs largely match till extension of 25%. The higher starting value of yarn 3 can be caused by a slightly longer sensor, or slightly different stitching or starting stretch. This shows the big influence of slightly varying parameters.

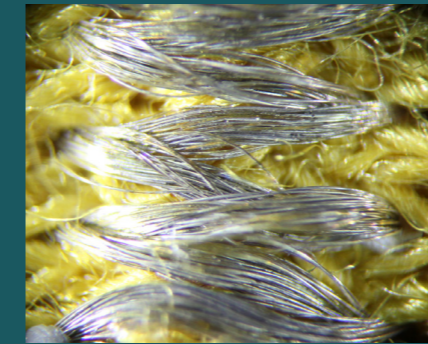
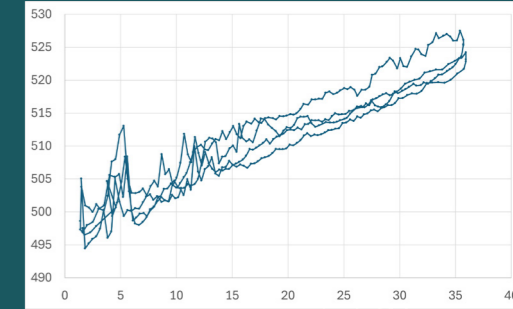
### Conclusion

Yarns 1 and 2 show a reasonably linear response with little hysteresis, but their gauge factor (sensitivity) is significantly lower than that of yarns 3 and 4. Yarn 3 and 4 show similar specification and a similar response with a slightly better performance of yarn 4. However it is expected that yarn 3 and 4 are the same type, it can be concluded that yarn 4 is the best option, thanks to its high linearity and good reproducibility. The observed hysteresis is acceptable, but will be reduced as much as possible in follow-up tests.



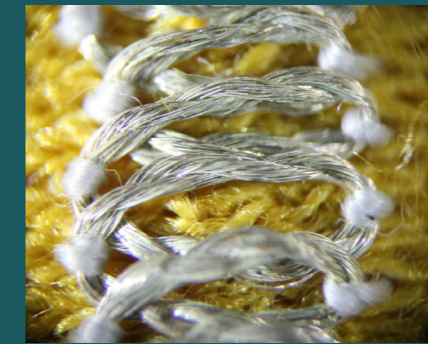
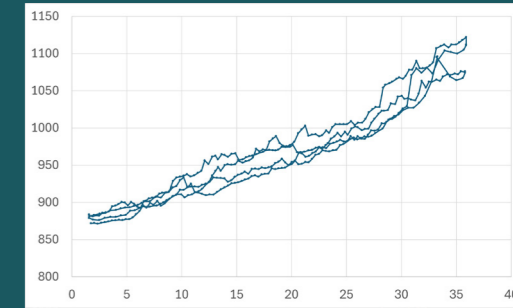
**SHIELDEX® 235 f 36 dtex Z130 (1)**  
235 f 235 filamenten  
**36 dtex**  
**2PLY** 2 strands twisted together

Resistance change: 500  $\Omega$  to 525  $\Omega$   
Gauge factor 0,14



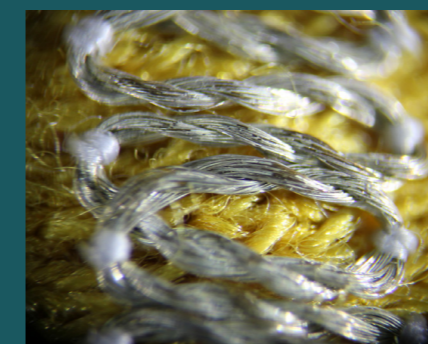
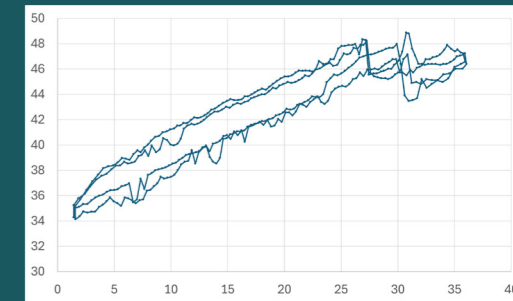
**Silver-Tech (AMANN) 120 Tex 28 (2)**  
**120 Tex** 1.000 meter weights 120 gram  
Moderate resistance  
Resistance 599  $\Omega$ /m

Resistance change: 875  $\Omega$  to 1100  $\Omega$   
Gauge factor 0,74



**SHIELDEX® Yarn 235 f 36 dtex 2PLY HC+ B (3)**  
**f 36** 36 filamenten  
**235 dtex** 10.000 meter weights 235g  
Resistance 48  $\Omega$ /m

High resistance  
Resistance change: 35  $\Omega$  to 49  $\Omega$   
Gauge factor 1,22



**SHIELDEX® Yarn 235 f 36 dtex 2PLY HC+ B (4)**  
Name on the spool: Silver yarn Dtex 604

Resistance change: 31  $\Omega$  to 45  $\Omega$   
Gauge factor 1,43

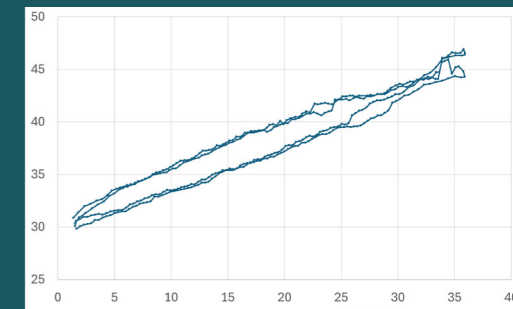


Figure 30. Four silver coated yarn types including their specifications and sensor response showed by a resistance ( $\Omega$ ) vs extension (%) graph

## 4.5 The influence of water

As previously described in the experimental studies, the use of anti-stretch paper was found to have a significant impact on the performance of the sensor after washing this paper. To determine which factor plays the most significant role, the paper or the water, measurements were taken on a sample before and after it was completely wet and dried again.

The graphs on the right show that wetting the sensor does indeed affect its performance (Figure 31, 32). Contact with water can affect the conductive yarns through oxidation or changes in microstructure (Stoppa & Chiolerio, 2014)(Cherenack & van Pieterse, 2012). The gauge factor decreases due to a smaller change in resistance and the flattening of the graph shows the influence on the work range.

This change is clearly measurable, but less significant than the influence of the anti-stretch paper. Chapter 7.1 Design scope discusses the extent to which this influence is taken into account in the rest of the project.

Figure 31. The resistance versus the extension performance graph before water contact

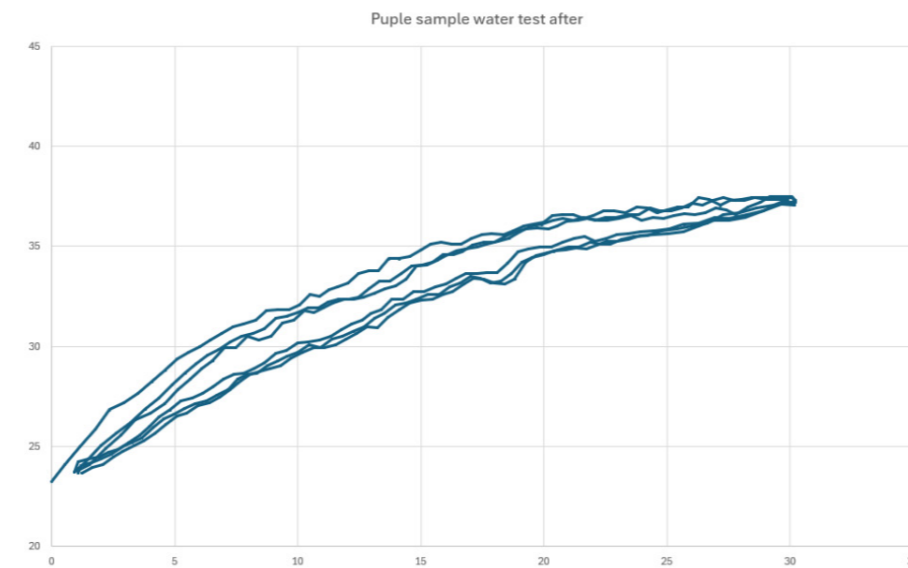
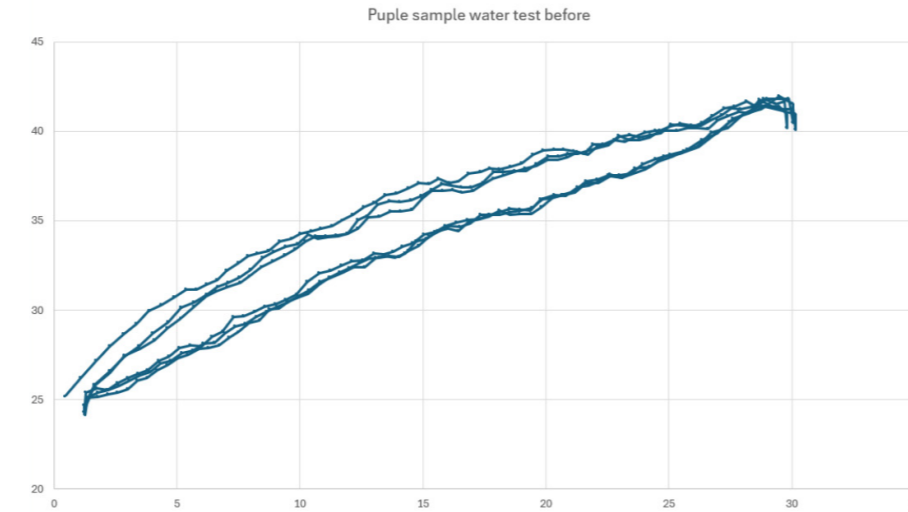


Figure 32. The resistance versus the extension performance graph after water contact

## 4.6 Chosen sensor properties

### Fabric

In order to make the sensor commercially viable, a commercially available textile was sought with properties similar to the nylon elastane fabrics that performed best in the experiments. This original fabrics came from sports leggings and was therefore not commercially available. Two more fabrics were tested with similar fabric structures where the purple one on the right came out as best based on the linearity and work range (figure 33).

The selected purple fabric has a thickness of 0.25 and consists of 78% polyester and 22% elastane, resulting in an elasticity of 2.9N at 35% stretch.

The measured resistance change results in a gauge factor of 2,27, which indicates a good measurable signal. Although there is some hysteresis, the start and end points of the stretch cycles consistently coincide. This means that the relative stretch (how far the sensor is stretched during a movement) remains reproducibly measurable. The hysteresis present therefore has only a limited and non-critical influence on the functionality of the sensor.

### Pattern

The experimental studies showed that a single zigzag with a density of 0.8 gave the best performance due to good linearity, reproducibility, and a sufficient gauge factor. However, pre-stretching the fabric by approximately 25% during production ensures that the final sensor exhibits both the low tolerances of the 0.8 density while it has higher density resulting in a bigger resistance change. This makes this configuration the most suitable choice for the final pattern.

### Yarn type

SHIELDEX® Yarn 235 f 36 dtex 2PLY HC+ B will be used (labeled as Silver Yarn Dtex 604) as the conductive yarn, as this type of yarn performed best in previous experiments and offers a stable electrical response during repeated stretching.

The graph in figure 33 on the right shows the performance of the sensor with the above composition, which will be used as sensor for the project.



Strechability 2.9N  
Thickness 0.28mm

Gauge factor	Linearity	Hysteresis	Repeatability
2,27	0,96	16.31%	0.43%

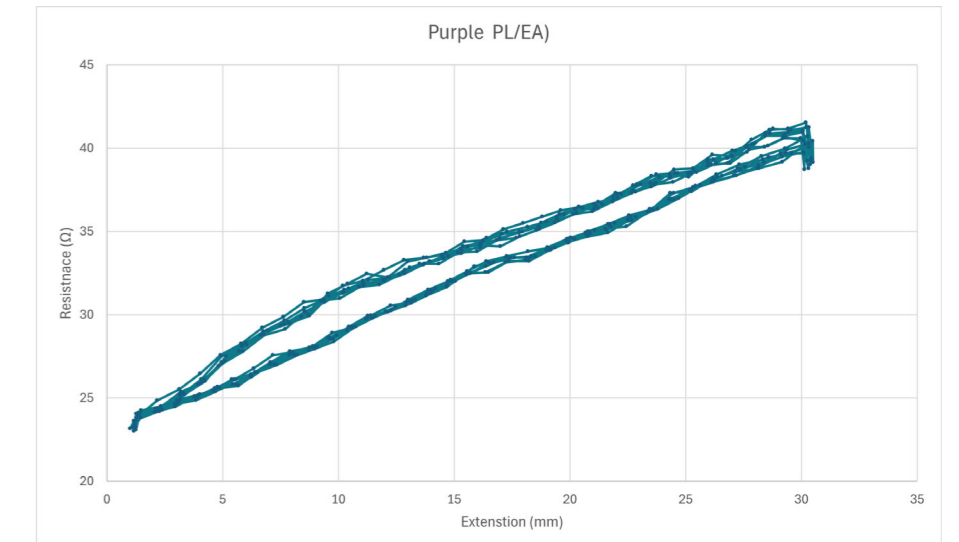
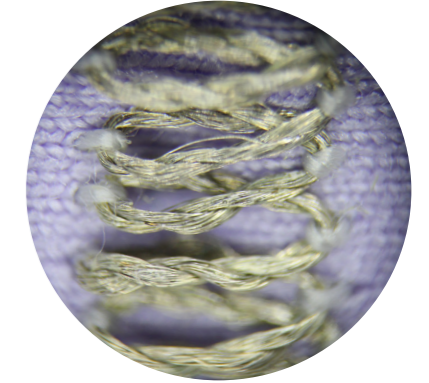


Figure 33. The performance graph of the selection combination of fabric, yarn type and pattern structure

## 4.7 Discussion and conclusion

### Discussion

The results show that a well-functioning textile stretch sensor needs a careful balance between sensitivity and reliability. For that reason, the focus was on selecting a sensor design that delivers stable and predictable measurements, rather than maximum sensitivity.

The influence of water on sensor performance was measurable, but smaller than the effect of contact with water when using anti-stretch paper. This emphasizes the importance of production processes and supporting materials in the development of textile electronics.

A limitation of this study for the project is that the measurements were performed under controlled, uniaxial strain. In practical applications, bending, torsion, and prolonged stress also occur. The behavior of the sensor under more complex deformations must also be investigated to make it suitable for taking measurements on joints, in this case the knee.

### Conclusion

This research has shown that the performance of a textile strain sensor is influenced by the choice of fabric, yarn pattern, and conductive yarn type. Fabrics with an average thickness and a composition of polyester or nylon with elastane ensure effective strain transfer, good rebound, and reproducible measurements. Fabrics that are too thin or too thick lead to inconsistent strain transfer or reduced linearity (research question 1).

In terms of pattern, a single zigzag pattern with a stitch pitch of 0.8 mm applied at 25% strain proved to offer the best balance between linearity, hysteresis, and repeatability. Denser patterns increased sensitivity but were also more sensitive to production tolerances (research question 2).

Of the yarns tested, SHIELDEX® Yarn 235 f 36 dtex 2PLY HC+ B labeled as Silver Yarn Dtex 604 delivered the best performance, with low base resistance, high gauge factor, and stable measurement cycles. The final sensor configuration achieved a gauge factor of 2.27, linearity of 0,95, hysteresis of 16,31% and repeatability of 0,43% which are all within the predefined limits. This makes this selected sample suitable for further development into a wearable sensor.

# TAKEAWAYS & IMPLEMENTATION

## Key takeaways

### Testing setup and variables

- Important variables for sensor performance are: work range, gauge factor (GF), linearity, hysteresis and repeatability.
- For reliable knee angle measurements, the sensor must:
  - Be sufficiently sensitive for at least 0–130° flexion.
  - Exhibit a linear and predictable resistance change.
  - Show limited hysteresis.
  - Be mechanically stable and provide reproducible results.

## Implementation

When evaluating and selecting textile strain sensors, the focus was on linearity and reproducible measurements within the relevant range of knee movement (0–130°).

### Fabrics

- The thickness and stretchability of the fabric influence the stability and amount of transmission of stretch to the conductive yarn.
- Fabrics with average stretch, but especially an average thickness provide the best combination of linearity and sensitivity. A blend of polyester/nylon and elastane came out as the best material composition.

The commercially available polyester-elastane combination will be used as the base material because it showed the highest linearity, reproducibility and gauge factor during the experiments.

### Patterns

- The zigzag pattern determines contact points and affects linearity and sensitivity.
- A density of around 0.8 mm showed lower sensitivity, but good linearity and reproducibility due to lower sensitivity to production tolerance.
- A single zigzag pattern gives the most reliable, linear response. A double zigzag theoretically increases sensitivity, but reduces linearity in practice because of the big influence of production tolerances.

A single zigzag with a stitch density of 0.8 mm, applied at 25% strain, will be used for the sensor pattern. This pattern offers the best balance between linearity, reproducibility, and sufficient sensitivity, and minimizes variations due to manufacturing tolerances.

### Conductive yarn types

- Yarn selection is important for baseline resistance, sensitivity, and reproducibility.
- Variation in thickness, construction, and filaments significantly affects performance.
- Single plies or thicker yarns (e.g., Silver Dtex 604) seem to have more stable contact networks, better linearity, and reproducible response.

SHIELDEX® Yarn 235 f 36 dtex 2PLY HC+ B, labeled as Silver Yarn Dtex 604, is chosen as the conductive yarn because of its good performance because of its low base resistance, high gauge factor, linear response, and high reproducibility.



## 5. Field research

In this chapter, interviews were conducted with various stakeholders within the rehabilitation system to gain more insight into the rehabilitation process from different perspectives and to assess the potential of the knee sensor sleeve.

### 5.1 Patient's perspective

### 5.2 Physical therapist's (local) perspective

### 5.3 Orthopedist and physical therapist's perspective

### 5.4 Discussion and conclusion

To gain more insight into the rehabilitation process from different perspectives and to assess the potential of the knee sensor sleeve so that it can be optimally adapted to practice, a study was conducted.

The aim of this study was to answer the following questions:

1. What is the rehabilitation process like after knee surgery/injury, and how is progress currently monitored by patients, physical therapists (PT's), and orthopedists?
2. What needs, wishes, and challenges do patients and healthcare professionals experience in measuring, monitoring, and supporting recovery during knee rehabilitation?
3. How can a textile knee sensor sleeve be effectively designed and applied to support the rehabilitation process?

To gather this knowledge, interviews were conducted, as these, through specific questions, can give in-depth insight into personal experiences, needs, perspectives, and practice methods.

For the third question the concept of the textile knee sensor sleeve was explained, with its purpose of continuous monitoring during exercises. Exactly how the sleeve would be used was left open, allowing the interviewee to express their opinions on its benefits, concerns, and wishes.

One patient was interviewed who had completed their rehabilitation and one patient who is still undergoing rehabilitation. In addition, a local physical therapist from Fysiotherapie MTC De Viergang in Pijnacker and an orthopedist and physical therapist from the Reinier Haga Orthopedic Center in Zoetermeer were interviewed.

The research questions and consent form can be found in the appendix B.

## 5.1 Patient's perspective

### Experience & background

Both patients underwent complex knee surgery (meniscus and cruciate ligament problems).

Rehabilitation was long (6 to more than 12 months) and intensive, involving several phases:

- Period of immobilization (brace or rest)
- Building up mobility (gradual bending)
- Strength and stability training
- Functional recovery towards sports or daily life

Both patients had to undergo a second operation due to scar tissue or the meniscus slipping back into place.

Initially, both were highly motivated, mainly due to their sporting goals and normal mobilization, but the process was described as slow and frustrating. *"You feel like you're starting all over again."*

### Guidance & appointments

In both cases, the physical therapist played a central role in rehabilitation. On average, patients attended physical therapy 2–3 times a week, where their progress was assessed and exercises were adjusted. The orthopedist was mainly seen in the initial phase and in case of complications (check-ups after 2, 6, and 12 weeks, then every 3 months).

Patients indicated that appointments with the orthopedist were often superficial *"Keep exercising"*, while the physical therapist was much more practically involved.

### Measuring progress

Progress was assessed visually and subjectively. Sometimes a goniometer, a protractor used to measure the angle of a joint, was used, but this was done irregularly. No data was recorded outside the physiotherapy practice. At home, patients did not track their progress, except perhaps by "feeling" whether they were improving or by looking how far they could bend their knee under a chair for example.

## 5.2 Physical therapist (local)

### Exercises & self-monitoring

The exercises evolved from light mobility exercises to strength and stability training. In the early stages, this included lifting the leg, moving the ankle, and light bending and stretching movements. Later on, this included more squats, lunges, leg presses, and balance exercises. Most of the exercises were standard and familiar, so remembering was not a problem, but performing and getting the dosage right was. A common problem was overexertion: wanting to build up too quickly, which led to fluid retention, stiffness, and/or scar tissue.

### Use of aids

In some cases, a brace is used directly after surgery. The patient with meniscus problems had to wear a splint brace for six weeks, which severely restricted mobility. The patient with meniscus and cruciate ligament problems had a brace for nighttime use but did not wear it because it was uncomfortable.

### Feedback on the sensor sleeve concept

The patients were introduced to the concept of the knee sensor sleeve: a wearable knee sleeve designed to track the movement of the injured knee and provide information on flexion, extension, and overall activity, with the aim of giving insight into rehabilitation progress. Patients responded positively to the concept. Patients were positive about the idea of a textile knee sensor sleeve. They see potential in objective progress measurement (flexion, extension, activity) and would be interested in data such as degrees, trends, and comparisons with previous weeks. Comfort is the most important requirement; it must not pinch. There were doubts about the usefulness and comfort of wearing the knee sleeve throughout the day.

### Patient profile and type of knee problems

He mainly treat anterior cruciate ligament and meniscus problems, and sometimes medial collateral ligament injuries. The age of patients varies greatly, but most cruciate ligament patients are young adults (up to 25 years old). After that age, surgery is only performed in cases of high sports activity or severe instability. Patients are often athletic young people or young adults who want to return to their sport.

### Rehabilitation process: structure and duration

Full cruciate ligament rehabilitation takes about 12 months. Recovery has distinct phases, depending on the type of surgery. If the meniscus needs to be sutured, the patient is not allowed to bend the knee more than 90° for the first 6–12 weeks. Without meniscus suturing, the knee can bear weight more quickly. The physical therapist views rehabilitation as a training program that progresses from restoring range of motion to strength to explosiveness to sport-specific performance.

### Pre-operative phase

Ideally, the physical therapist would like to see patients three months before surgery to strengthen muscles, especially the hamstrings. This increases the chances of a successful operation:  
*“The hamstrings must be of a certain thickness to make a strong cruciate ligament.”*

In practice, this does not always happen, usually for financial reasons or because patients come to the physical therapist after the operation. This means that an opportunity to better prepare for rehabilitation is missed.

### Early postoperative phase

He prefers to see the patient for the first time within 3 days after surgery. The focus is then on muscle activation via electrical muscle stimulation (EMS) to relearn muscle control. This is used in both unloaded and loaded exercises to stimulate neuromuscular control. After that, the focus is on regaining movement through manual mobilization:  
*“People find it difficult to hurt themselves, so I help them through it.”*

### Training structure & individual adaptation

There are standard exercises such as squats, lunges, and deadlifts, but the program is highly personalized, especially in the later phases. Then, the focus is on variation and progression through functional and sport-specific movements: for a volleyball player, the focus is on jumping, but for a hockey player it is more on sprinting, braking, and explosive acceleration.  
*“You have a specific goal. In the final phase, for example, explosiveness; then I tailor the exercises to that.”*

Attention is also paid to symmetry and execution.

*“What is the difference between the left and right leg?”*

The focus here is primarily on the range of motion and balance between the left and right leg, to promote balanced strength and correct movement patterns.

### Monitoring & testing

Measurements are taken at 3, 6, 9, and 12 months using the VALD dynamometer (figure 35). This measurement instrument is placed on the ankle and measures Range of Motion (ROM) and strength (quadriceps/hamstring). For the ROM it uses an IMU (accelerometer and gyroscope) to track the rotation of the lower leg and calculate the knee angle. Jump tests are also performed to assess performance and strength (landing and symmetry). The most important metrics are ROM (especially in the initial phase) and Limb Symmetry Index (LSI); difference between the injured and healthy leg. Monitoring via these tests helps to keep track of the progress and determine when the patient can resume sports activities.

### Challenges in monitoring

The biggest bottleneck at the moment is the lack of time and limited capacity.  
*“If you want to test someone properly, you need 1 to 1.5 hours, but that’s difficult to fit into the schedule.”*  
 Sometimes measurements are forgotten or postponed due to busy schedules. In addition, the tests are snapshots, so they do not provide a picture of daily progress. The VALT meter also provides a lot of raw data that can sometimes be difficult to interpret. The physical therapist recognizes the advantage of monitoring during exercises:  
*“The goal is the same, but your product makes it much more manageable.”*

Figure 35. The VALD dynamometer can measure ROM using an Inertial sensor (DynaMo, n.d.)



### Patient motivation and behavior

Motivation is an very important factor for recovery:

*“The more motivated you are, the greater the chance of success.”*

Patients go to the physical therapist 2 to 4 times a week. The frequent guidance keeps the process under control and structured.

Still, he sees differences in discipline: Some patients make excuses (“no time”). Objective data can help make their commitment a topic of discussion.

### Communication with other healthcare providers

Communication with the orthopedist takes place via Cilo, a medical chat app. After 6 weeks and then at 3, 6, 9, and 12 months, he sends updates on progress. This involves sharing data on, for example, the range of motion of the knee, strength, pain level and performance during exercises.

### Termination and prevention

The patient is “ready” when the test results are good and he/she feels mentally ready. After 12 months, the cruciate ligament is 90% mature, which is considered sufficient.

A prevention plan is often drawn up for the period after discharge, recommending that the patient continue strength training at least twice a week and return after 3–6 months for a retest. In case of mental barriers, he sometimes calls in a sports psychologist.

### Use of braces and aids

During rehabilitation, braces are preferably avoided unless medically necessary, because a brace reduces functional load and muscle building.

*“During rehabilitation, you want to put functional strain on the knee.”*

### Important parameters

- Flexion and extension angles (ROM)
- Knee valgus movement (the inward tilting of the knees): important for injury prevention
- Symmetry between left and right knee
- Feedback during the exercise (real-time) is considered even more valuable than feedback afterwards.

### Application and context of a smart knee sensor band

The knee sensor sleeve has the greatest potential in early rehabilitation when measuring flexion/extension and gait pattern. The use of a sleeve on both knees for comparison and visual feedback (split screen) is very valuable.

He sees the most value in practical use during exercises, less value “in everyday life”:

*“You can wear it at home, but then you only see the results afterwards.”*

### Practical requirements and preconditions

- Ease of use: quick to put on, intuitive to use, easy to combine with existing routines.
- Washability: important for reuse (hygiene with multiple patients).
- Price sensitivity:  
*“If it costs 30 euros, we can use it every day. If it costs 300 euros, it's more for the practice.”*
- Feedback form: graphs and comparison between knees are ideal.

## 5.3 Orthopedist and PT

### Types of surgery and patient population

The most common knee surgery is arthroscopy (meniscus injury), followed by anterior cruciate ligament reconstruction and knee replacement.

The ages of the patients ranges from young (16 years old) to old (80 years old), so it is a broad target group with varying needs and recovery rates.

### Factors that influence recovery

The type of surgery strongly determines the duration and intensity of rehabilitation:

- Arthroscopy: recovery within a few weeks.
- Anterior cruciate ligament:  $\pm$ 9 months of rehabilitation.
- Knee replacement: 6–12 months to full recovery.

In addition, personality and motivation are seen as crucial success factors. How someone deals with pain, discipline, and consistency in exercising largely determines the outcome.

In addition, swelling, bruising, severity, and duration of the surgery also play a role in how quickly the patient can recover.

### Current follow-up & monitoring

Recovery is currently monitored at fixed check-up times, not continuously:

- 2 weeks: Wound check and removal of stitches.
- 6 weeks: Function check (bending/stretching).
- After that: every 3–4 months or only after a year, depending on recovery.

During check-ups, the main focus is on the degree of flexion and extension, knee stability, pain level, and wound healing. There is no continuous or dynamic monitoring between these check-ups.

*“We don't actually monitor it, only at peak moments.”*

There is no structural contact between the orthopedist and the local physical therapist, only occasional communication via Cilo.

*“If I don't hear anything, I assume that everything is going well.”*

### Role of the physical therapist (at the center and at home)

Immediately after surgery, the physical therapist within the orthopedic center sees the patient on the same day to practice initial mobility. Movement is still very limited, so the focus is on daring to move and building confidence. After discharge, the patient goes to a local physical therapist, who supervises the recovery.

The physical therapist in the orthopedic centre sometimes uses a goniometer to demonstrate the range of motion, but measurement is mainly visual and subjective.

### Home rehabilitation & motivation

Exercising at home is important but difficult to monitor. There is no objective data on what patients do at home. Patients often overestimate or underestimate how much they practice

*“Practicing a lot means twice a day for one person, five times a day for another”.*

Both orthopedists and physical therapists see greater control and insight as valuable:

*“If you know how much someone is actually doing, you can better understand why recovery is or isn't going well.”*

Digital tools such as exercise apps or gamified programs are seen as motivating and effective:

*“Those apps where you do exercises on the TV really contribute to better recovery.”*

### Use of braces and splints

Braces are used to restrict movement or provide protection, not as support. Patients usually wear the brace for 6 weeks to 3 months. Extension splints are also sometimes used, especially for injuries where bending is not yet permitted.

The biggest challenges are braces slipping down, especially in people with wide or “pyramid-shaped” legs. Comfort, hygiene, and wearability are also important for compliance with therapy.

### Need for measurement data and feedback

Both (orthopedist and physical therapist) see value in data about:

- Range of motion (flexion and extension angle).
- Frequency and duration of movements.
- Any swelling throughout the day.

Monitoring would help to:

- Objectively track recovery.
- Assessing therapy compliance.
- Providing patients with feedback and motivation.

It is important that the system:

- Is comfortable, affordable, and accessible.
- Displays data clearly (graphs, progress, notifications).
- Does not take too much time or effort to set up.

### Motivation & behavioral change

Both orthopedists and physical therapists emphasize that feedback and gamification stimulate recovery:

*“Compliments (well done!), progress badges, notifications (time to move) make it more fun.”*

*“It’s just like with ski apps or Garmin: people get motivated by numbers and compliments.”*

There is a great opportunity to convert motivation problems into behavioral activation through design.

### Practical and technical considerations for a smart brace

- Comfort and fit are important; the brace should feel like a sock or legging
- Location of electronics: preferably on the outside of the thigh. There is less pressure there.
- Hygiene: It should be easy to clean (especially in case of wound leakage).
- Adjustability: Individual calibration is required (bend/stretch zero points differ per person).
- Stability: The brace should not shift.
- Affordability: It must remain inexpensive.
- Wearing time: Preferably usable all day without discomfort.

## 5.4 Discussion and conclusion

### Discussion

This study shows that there is a clear gap between the current monitoring methods and the need for insight into the rehabilitation process. The sensor sleeve is seen as a promising solution for collecting objective data and involving patients more actively in their recovery, for example through feedback and progress insights.

A limitation of this study is the small number of participants, which means that the results are not fully representative of all patient groups or physical therapy practices. The insights gained so far give a first impression of the applicability and opinions of the sensor sleeve, but cannot be generalized.

Future research should focus on including a larger and more diverse group of patients and healthcare professionals. Multiple physical therapists and patients from different practices should be interviewed. This will help to better investigate how rehabilitation processes vary, what variations exist in treatment methods, and how patients experience the current guidance and exercises. This could lead to a more complete understanding of the context in which the knee sleeve can be used and how it can meet the needs of both patients and healthcare professionals.

### Conclusion

The rehabilitation process after knee surgery is long, in phases, and dependent on the type of procedure. The physical therapist plays a central role in this process by giving frequent guidance, while the orthopedist is mainly involved at periodic check-ups. Progress is mainly assessed visually and subjectively, supplemented by periodic measurements like range of motion or strength measurements. Outside the practice, recovery is hardly monitored (Research Question 1).

Patients and healthcare professionals experience a clear need for objective and continuous measurement data, particularly regarding flexion, extension, symmetry, and load build-up. Challenges currently lie in lack of time, limited measurement moments, interpretation of data, and adherence to exercises at home. Motivation and overload appear to be problems as well (Research Question 2).

A textile knee sensor sleeve can address these limitations by enabling comfortable, reliable, and continuous monitoring. For effective application, wearing comfort, ease of use, clear feedback, and relevant data for both the patient and healthcare providers are important.

# TAKEAWAYS & IMPLEMENTATION

## Key takeaways

### Rehabilitation process & monitoring

- Rehabilitation after knee surgery is a long process (6–12+ months) and consists of phases: mobility --> strength --> stability --> functionality/ sports.
- Patients, physical therapists, and orthopedists feel that monitoring is currently fragmented and subjective: measurements are mainly visual.

- Check-ups with the orthopedist are infrequent, and progress in daily life is not monitored.
- There is no objective data on exercises at home, which often leads to overuse or underuse.



## Implementation

The knee sensor sleeve will focus on objectively measuring flexion and extension, replacing the current subjective checks and objective snapshots. This can help track progress and prevent overuse and underuse.

### Patient needs

- Patients experience rehabilitation as long, difficult, and frustrating, with a lot of uncertainty about their progress.
- They want objective feedback on flexion/extension and trends over time

- Comfort is important: a brace or sleeve should not pinch, slip down, or cause irritation.
- There is some doubt about wearing the sensor sleeve all day long, as daily activities rarely reach maximum knee angles, limiting the relevance of the measurements. Use during exercises is therefore preferred.



The sensor sleeve will prioritize comfort, simplicity, and minimal irritation, which will be tested to ensure a secure fit without slipping and suitability for repeated use. Research will also focus on presenting the data clearly and simply, helping patients feel confident in their progress and reducing uncertainty.

### Physical therapist needs

- Reliably measure ROM (flexion/extension),
- Left-right comparison (LSI) for symmetry
- Real-time feedback during exercises
- More insight between sessions to monitor therapy compliance
- The biggest challenges are lack of time, snapshot measurements, and difficult interpretation of raw data.

- A sensor sleeve is particularly valuable in the early stages and during functional exercises (gait, squats, lunges).
- A sleeve for both knees at the same time (comparative image) is considered very useful.



The sensor sleeve will focus on providing reliable ROM data and left-right comparison. Research will be conducted into how real-time feedback can best be integrated into the exercise situation, so that physical therapists can monitor technique and load. Data processing will be developed so that physical therapists can gain insight quickly and efficiently, without additional workload.

### Orthopedists' needs

- Check-ups are currently snapshots without insight into daily recovery.
- The most important parameters are ROM, pain, swelling, and functional mobility.

- A continuous monitoring system helps provide insight into treatment adherence, recovery speed, and abnormal patterns.
- Digital tools and gamification are considered effective and motivating. Systems must be simple, affordable, and quick to use.



Research will examine the role of gamification in rehabilitation. Although the orthopedist mentioned several relevant parameters, he indicated limited interest in continuous progress updates, preferring a summary before checkups or when issues arise. How progress and issues will be communicated will be determined later in the process.

### Overarching user needs

- Objective, understandable data (graphs, trends, badges).
- Real-time feedback during exercises.

- Comfort, stability, and correct positioning are essential (braces often slip down).
- Hygiene and washability are important requirements.
- Personal calibration is necessary, as everyone's zero point and mobility differ.



The sensor sleeve will focus on objective, clear, and motivating feedback tailored to all user groups. Research will be conducted into materials, elasticity, antislip methods, and design to maximize comfort and stability. The difficulty of washability is discussed in the chapter 7.1 Scope.



Figure 36. Defining and checking of the angles of the validation setup

## PHASE 2

# DEFINE

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In this phase, design opportunities were developed based on a visualized patient journey. Defining the scope, problem, target group, and design requirements formed the focus of the project.

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- 6. The rehabilitation system and process
- 7. Focus

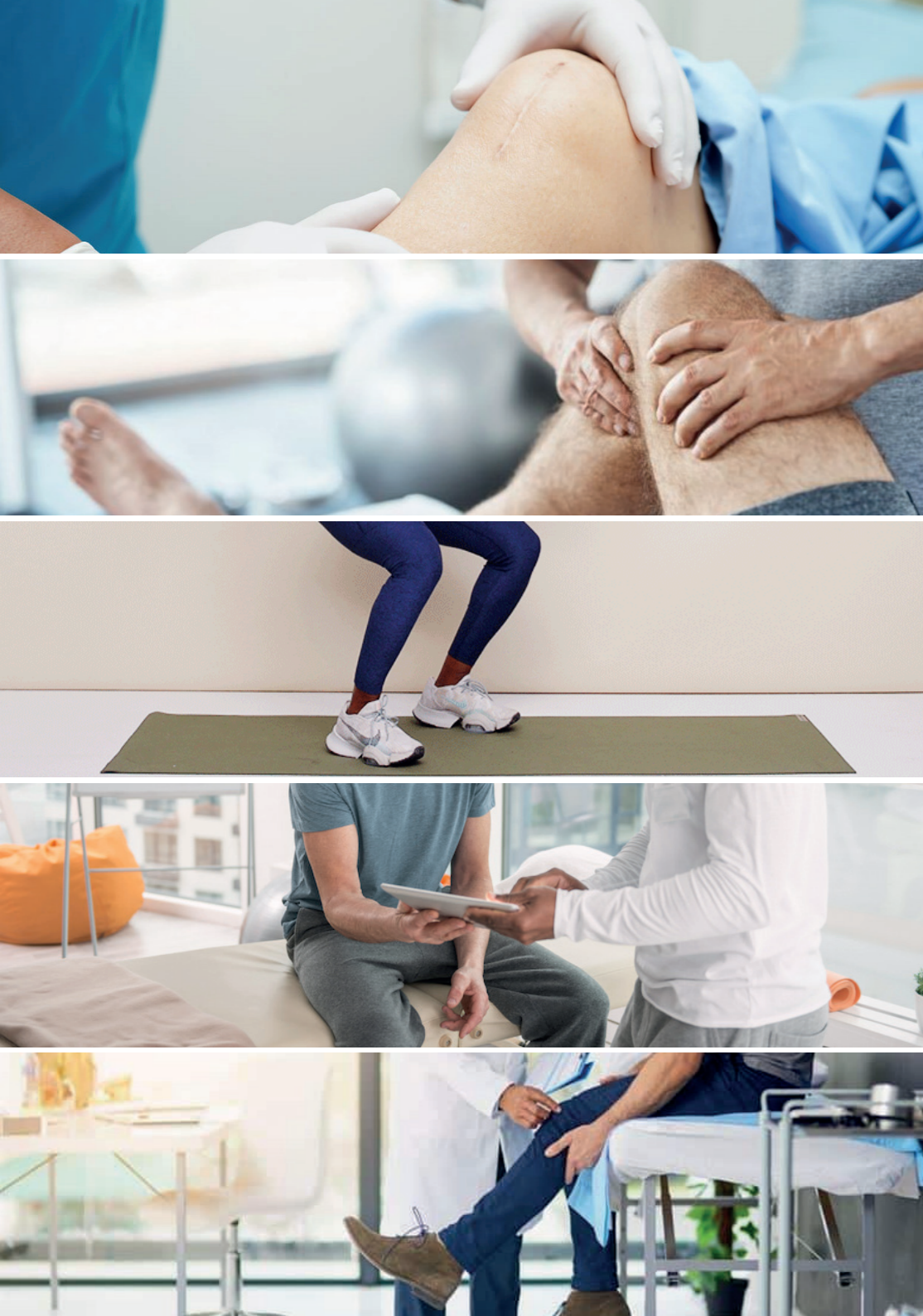


Figure 37. Snapshots of the different phases of the rehabilitation process

## 6. The rehabilitation system and process

This chapter describes the current rehabilitation system based on the interviews and explores how it may change with the implementation of the knee sleeve. In addition, the patient's rehabilitation journey is mapped out to identify where and how the knee sleeve can provide the most value.

- 6.1 The system
- 6.2 Patient journey
- 6.3 Design opportunities

### 6.1 The system

#### The current system

In the current rehabilitation system (figure 38), the patient is central and forms the hub of most interactions. The patient has intensive contact with the physical therapist throughout the entire rehabilitation process. The physical therapist gives instructions, supervises exercises, and receives feedback from the patient about the progress of their recovery.

The orthopedist plays a more peripheral role in this system. Contact between the patient and the orthopedist mainly takes place during scheduled check-ups after surgery. If necessary, the orthopedist communicates with the physical therapist to provide advice on the further course of treatment or adjustments to the treatment.

Family and friends mainly have direct contact with the patient. They support the patient during the rehabilitation process, but generally do not have any interaction with the healthcare professionals.

#### The new part

In the new system (figure 38), the existing rehabilitation network is expanded with a technological system, external parties, and the role of the designer.

The patient wears the knee sensor sleeve, which allows them to interact directly with the technological system. The knee sleeve collects the patient's movement data and sends it to the cloud environment via the app interface. In the cloud, the data is processed by the data analysis algorithm, after which the generated insights are sent back to the app interface.

The app interface is the central point of communication between the technological system and the human actors. Both the patient and the physical therapist have access to the app and can view the processed data.

The physical therapist uses the app interface to gain insight into the patient's progress. If necessary, the physical therapist can share relevant information with the orthopedist, who can then gain remote insight into the progress of rehabilitation.

Family and friends stay in touch with the patient. In the new system, they can be indirectly involved via the app interface, for example by receiving updates or supporting the patient in using the system.

The knee sleeve is purchased by the patient from a medical supply store on the advice of a physical therapist. The product is manufactured by a manufacturer and delivered to the medical supply store via a medical wholesaler.

The software/app developer has no direct interaction with the rehabilitation process, but maintains and develops the app interface, cloud environment, and data analysis algorithms. This party receives input from users and processes it into updates to the system.

As a designer, I am responsible for the design of the knee sensor sleeve and the app interface. I have contact with both direct and indirect users; patients, physical therapists, and orthopedist, to gather insights that are used in the design of the system.

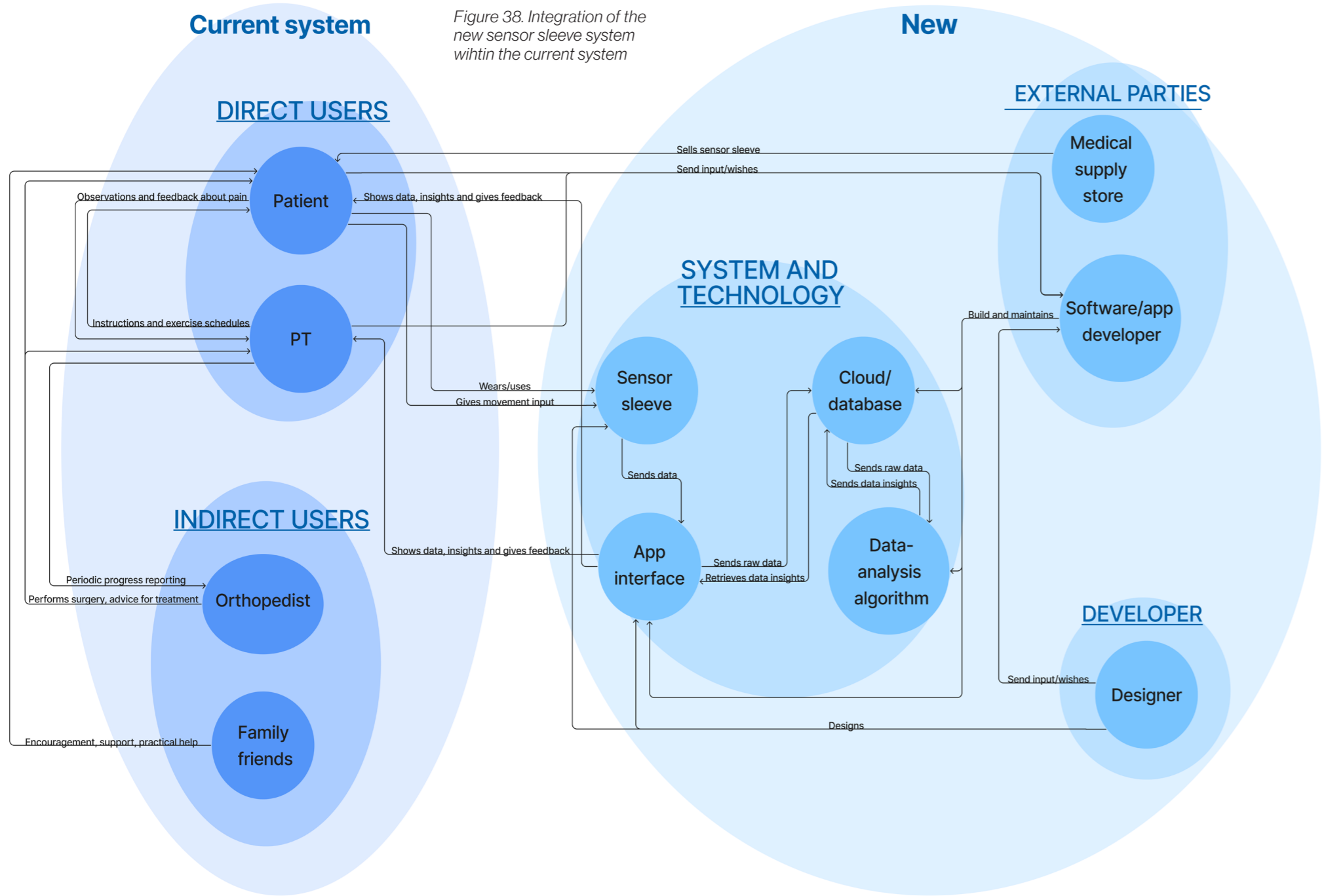


Figure 38. Integration of the new sensor sleeve system within the current system

## 6.2 Patient journey

To visualize the patient's journey (figure 39) after knee surgery, the Journey Mapping method from the Delft Design Guide (Van Boeijen et al., 2020) was used. This method gives an overview of the various steps, touchpoints, and stakeholders involved throughout the entire process. The patient journey was developed based on interviews with two patients, a local physical therapist, and an orthopedist and physical therapist from the orthopedic center. While every patient's recovery process is unique, this journey map reflects the insights gathered from these interviews. However, it should be noted, that the small number of interviews limits the generalizability of this map. It represents a initial overview rather than a definitive or generally applicable patient journey.

The various phases and subphases are displayed vertically, with the corresponding touchpoints, emotions, challenges, and stakeholders horizontally.

**The first phase** includes the diagnostic and surgical process. The patient visits the general practitioner because of knee complaints. After being referred to the orthopedist, an examination and MRI scan are performed. Based on the results, surgery is scheduled and performed.

**The second phase** involves postoperative checkups. Directly after the surgery, evaluations are conducted by the orthopedist and physical therapist to check wound healing, swelling, and range of motion. If recovery doesn't progress as expected, a second surgery is sometimes performed.

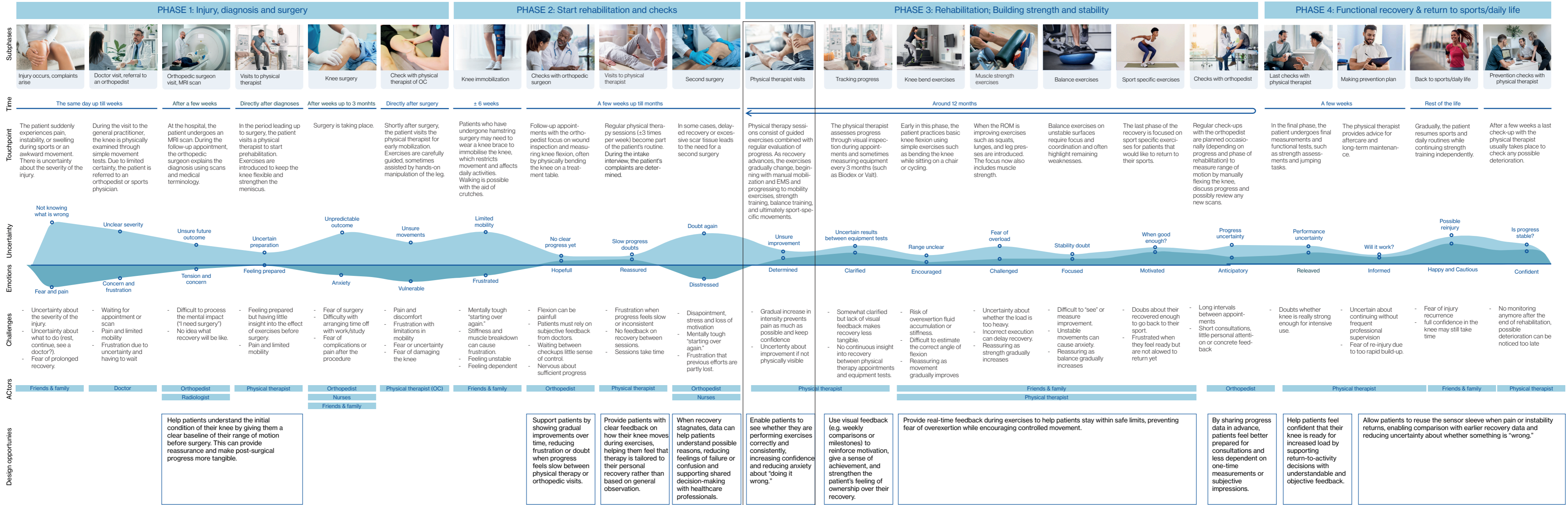
**The third phase** focuses on rehabilitation. The patient does flexion, strength, and balance exercises under the supervision of a physical therapist, partly at home. Progress is evaluated by the physical therapist and orthopedist, and the exercise program is adjusted based on the recovery progress.

**The fourth phase** consists of completion and prevention. The knee is almost recovered, and final checkups are taking place. A prevention plan is developed in collaboration with the physical therapist.

The bottom row of the journey includes the design opportunities. These provide insight into where and how the knee sensor sleeve can provide the most value in the rehabilitation process.

### PT session and exercises in detail

The patient journey gives an overview of the entire rehabilitation process after knee surgery or injury. Because the knee sleeve will offer the most value during physical therapy sessions, figure 40 zooms in on the various steps within a session. Figure 41 zooms further in on performing of the exercises, as this is the primary situation in which the knee sleeve is used.



See details Figure 40

Figure 39. Patient Journey

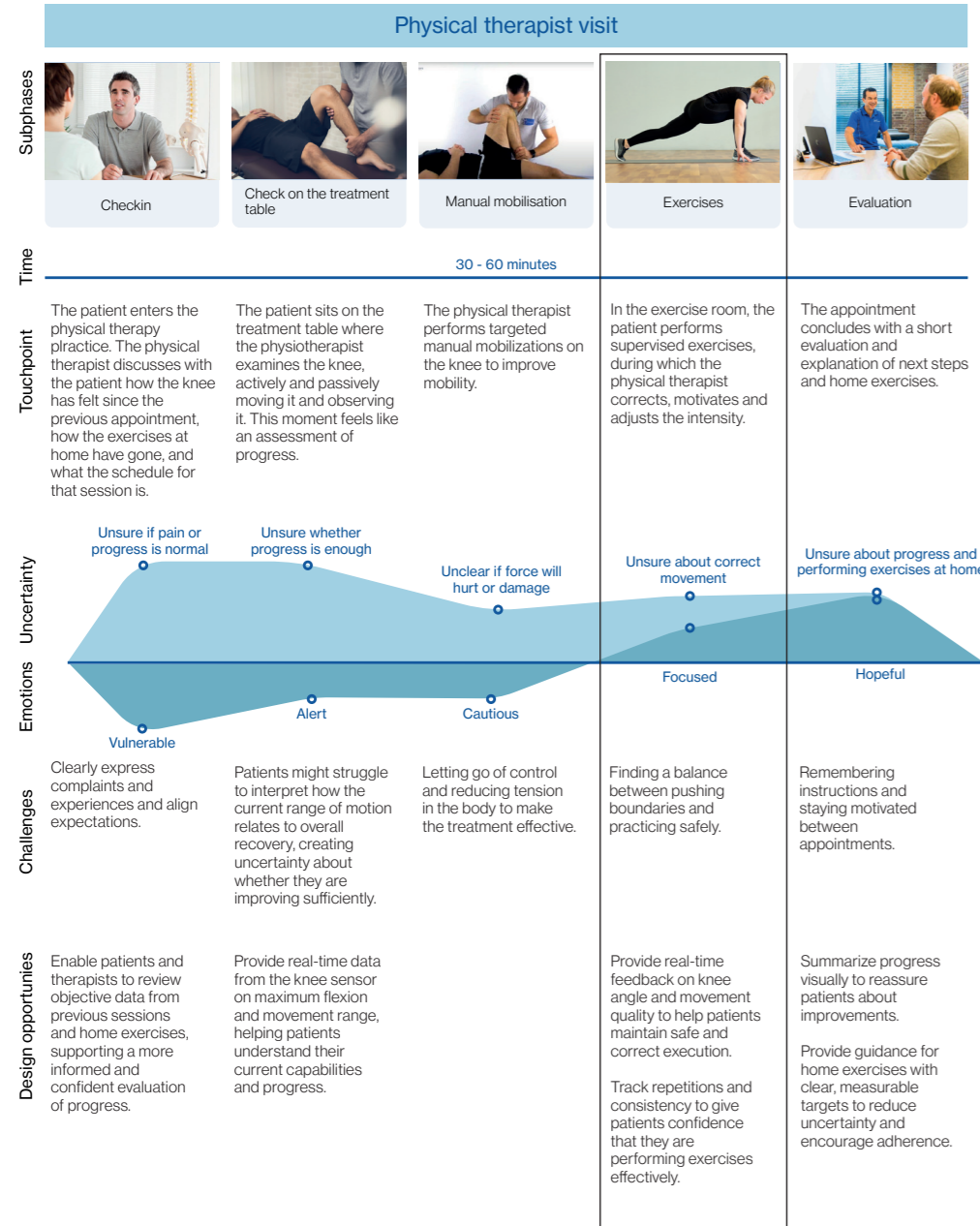


Figure 40 Zoomed in on a physiotherapy visit

See details Figure 41

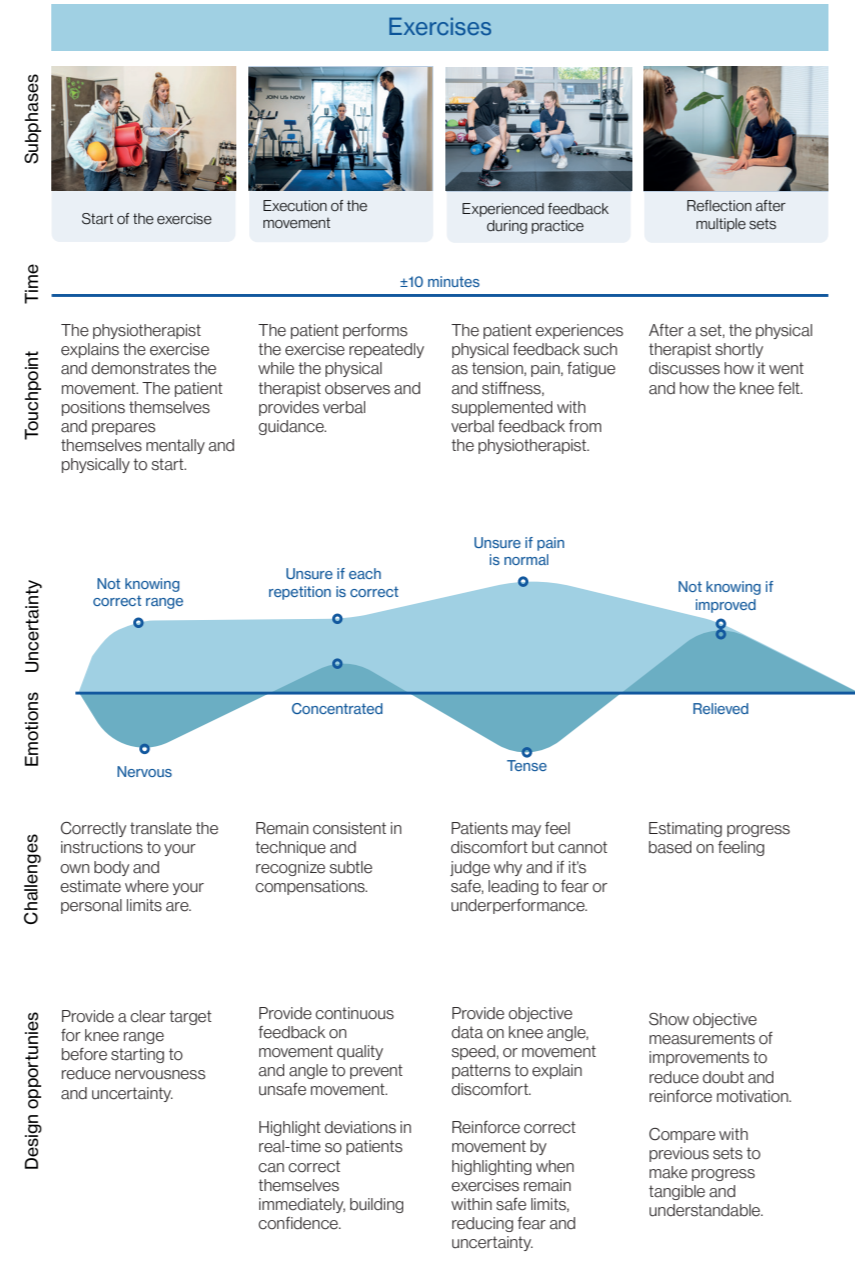


Figure 41 Zoomed in on a practice session

## 6.3 Design Opportunities

Throughout the rehabilitation process, patients experience emotions and uncertainties. The knee sensor sleeve offers opportunities to create more control, insight, and motivation during these moments. This chapter gives a description of how the patient's emotions and uncertainties develop during each phase and how the design can positively influence them.

### Phase 1

When the patient suddenly feels pain and instability during exercise, for example, fear and high uncertainty arise: what exactly is going on, and how serious is it? During the visit to the general practitioner and later the orthopedic surgeon, this uncertainty remains, but shifts to concern about the diagnosis and the consequences for daily life and sports. After the MRI scan, the patient knows more, but the future stays unclear and uncertain.

In the weeks before the operation, the patient starts preoperative physical therapy. The emotion changes to preparedness, but doubts remain about the current status of the knee.

**Design opportunity (1.1)** The sensor sleeve can be used here to take a baseline measurement of knee flexion before surgery. This objective data allows the patient to see how mobility develops later on, which can provide reassurance and make post-surgical progress more tangible.

### Phase 2

In the first few weeks after surgery, patients can experience frustration and uncertainty, especially when they have to use a brace and crutches that limit their mobility. Between check-ups with the orthopedist, patients often remain uncertain about their progress: is the knee moving enough? Is rehabilitation on track?

**Design opportunity (2.1)** The sensor sleeve can continuously gradual improvements over time. This can reduce frustration or doubt when progress feels slow between physical therapy or orthopedic visits.

During physical therapy, emotions are a bit more reassured, but doubts often remain because assessment is usually visual.

**Design opportunity (2.2)** The sensor sleeve can support physical therapists with movement data and feedback, enabling them to make more targeted adjustments and giving patients the feeling that therapy is tailored to their personal recovery rather than based on general observation.

When recovery does not progress and a second operation may be necessary, the patient can experience stress and worry.

**Design opportunity (2.3)** Objective data on the recovery process could identify signs of stagnation at an early stage, allowing for earlier and more informed intervention. Understanding these possible reasons can reduce the feeling of failure or confusion and can support shared decision-making with healthcare professionals.

### Phase 3

During physical therapy sessions, patients are often motivated to work on their recovery, but they can also experience a lot of uncertainty. They may wonder whether their pain or stiffness is normal, whether they are making enough progress, and whether they are performing the exercises correctly. Because progress is often measured based on feelings instead of objective measurements, patients can sometimes feel uncertain about how much pressure they can put on their knee while still recovering effectively.

**Design opportunity (3.1)** By enabling objective data on knee movement, like range of motion, consistency, and repetitions, the sensor sleeve can support both patients and physical therapists in getting a better understanding of progress. Reviewing data from previous sessions and home exercises helps to base conversations on objective data instead of subjective memories. This can reduce uncertainty and improve communication.

During the active exercise phase, uncertainty can increase. Patients may wonder whether each repetition is being executed correctly, whether the pain or tension they are experiencing is normal, and whether they are exercising safely without overloading the knee. Subtle compensations or inconsistencies in execution are easily overlooked, especially when fatigue sets in. This can lead to anxiety or reluctance during the exercises.

**Design opportunity (3.2)** Real-time information on knee angle, speed, and movement can help patients stay within the safe limits while exercising. Deviations can be noticed and mentioned directly, enabling patients to correct their movement right away. This can support correct execution and build confidence. By linking discomfort to objective movement data, patients can better understand their experiences.

Even after completing a set of exercises, uncertainty can remain. Patients can feel relief or fatigue, but often still wonder whether they have really made progress compared to previous sessions. Without concrete feedback, progress is difficult to track. This can affect motivation and self-confidence, especially when exercising independently at home.

**Design opportunity (3.3)** Visual summaries of progress per set and comparisons with previous sessions can make improvement tangible and understandable. By translating effort into measurable results, the sensor sleeve can increase motivation and give clear guidance for home exercises. This can reduce uncertainty and support long-term adherence to therapy.

During physical checks, like on the treatment table, patients may wonder whether their range of motion is enough and how this fits into their recovery process. They do not have a clear reference.

**Design opportunity (3.4)** By visualizing maximum knee flexion and changes over time, the sensor sleeve can help patients better understand their current capabilities and how these develop over multiple sessions. This makes individual measurement moments part of a bigger picture, which can increase confidence.

### Phase 4

At this stage, the patient wants to know whether they are ready to return to his sport. The final tests can cause nervousness, because of the importance of the decision-making moment.

**Design opportunity (4.1)** Sensor data can demonstrate that exercise is safe and that the quality of movement meets the criteria for return. This provides confidence and supports an objective completion of rehabilitation.

Afterwards, the patient may sometimes remain cautious, especially when resuming intensive activities.

**Design opportunity (4.2)** The sensor sleeve can be used when the patient experiences doubts or signs of relapse. By supporting return-to-activity decisions with understandable and objective feedback, the patient can get more confidence that their knee is ready.

The check-up after three to six months is usually positive, but there remains slight uncertainty about long-term stability.

**Design opportunity (4.3)** Comparative data with earlier recovery data can and reduce uncertainty about whether something is “wrong”.



Figure 42. Adding the anti-shift elastic bands

## 7. Focus

This chapter defines what is and is not covered within the project (the scope), what the current problem is, who the target group is, and what requirements the knee sleeve must meet.

- 7.1 Design scope
- 7.2 Problem definition
- 7.3 Target group
- 7.4 Design goal and requirements

## 7.1 Design Scope

This project has chosen to find a balance between feasibility and detailing. The final prototype will not yet be fully market-ready, but it will be developed in such a way that its ultimate functionality is clearly defined and can be tested.

The inner circle contains the components that are fully incorporated into the concept development. The outer circle contains topics that are being partially researched or developed. All elements outside these circles are outside the scope and will therefore not be addressed.

The main focus is on developing a functional and comfortable knee sensor sleeve. The sensor will be optimized within the capabilities of TU Delft, with the goal of generating reliable and repeatable data on knee flexion and extension. In addition, research will be conducted into how the sensor can be integrated into a knee sleeve.

The project has tested various types of silver-coated conductive yarns. However, no additional material research will be conducted on alternative conductive yarns. The impact of washing on the conductive yarns is outside the scope, as this is beyond the available resources and commercial solutions already exist or will be developed in the future. The product is designed with future scalability in mind, using commercially available fabrics and yarns. The production process itself will not be scalable, but there are market opportunities that will allow for scaling up at a later stage.

In addition to the technical aspects, attention will be also paid to the fit and comfort of the knee sleeve. These will be optimized as much as possible, but different sizes will not be developed and no medical certification processes will be performed.

Finally, data will be collected and processed with the working methods of current wearables as reference, but this full operation won't be pursued. It is being developed to such an extent that during the user evaluation test it can be demonstrated and tested how the knee sleeve will work. In addition, the layout of the app will be visualised in Figma, an interface design platform, to show how the interface will look like, but a fully working application will not be developed within the scope of this project.

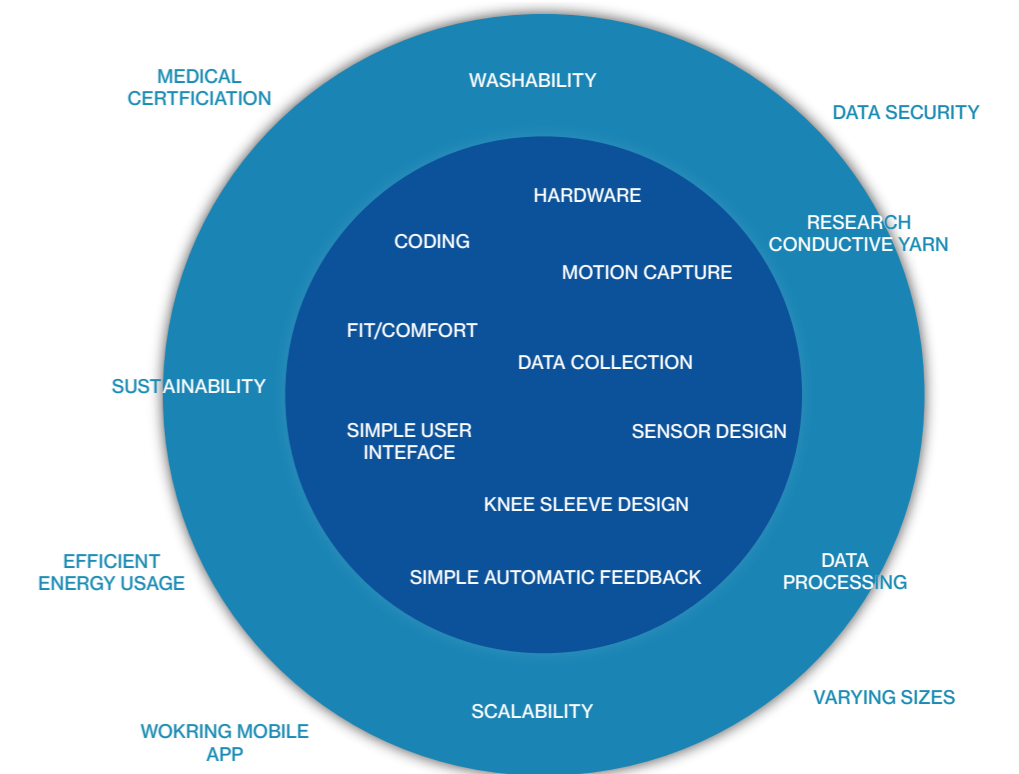


Figure 43. Design scope; within scope (dark blue), partly within scope (light blue), outside scope (outside circle)

## 7.2 Problem Definition

The recovery process after knee surgery is long, intensive, and requires collaboration between healthcare providers. In practice, however, rehabilitation progress is still mainly evaluated during physical appointments with a physical therapist or orthopedist. These measurements are often visual and subjective. The objective measurements that are sometimes done only provide a snapshot of the recovery status. Both outside and inside the treatment practice, objective data on how often, how intensively, and how correctly the patient is actually exercising is lacking.

This leads to a lack of continuous insight into the recovery process. Patients are unsure whether they are making progress or are overexerting themselves. Healthcare providers can only assess the home situation based on self-reporting and clinical situations subjectively. Moreover, communication between the orthopedist and the local physical therapist is limited and inconsistent, resulting in a lack of a complete overview of the rehabilitation process.

Existing technologies that can measure motion, like IMUs (Inertial Measurement Units) or optical systems provide accurate data. However, in practice they are complex, prone to drift, and impractical for long-term use outside the clinic. They need calibration, are relatively expensive, and provide more information than is needed for simple progress monitoring.

Previous research into textile-integrated strain sensors shows that they represent a promising alternative: lightweight, accessible, and potentially comfortable for daily use. However, such sensors have not been translated into practical, user-friendly products that can be worn long-term in the context of rehabilitation.

This creates the need for an accessible, comfortable, and reliable measurement system wearable that can continuously record knee flexion and movement in general, even outside of a clinic. A textile knee sleeve with an integrated strain sensor can be a solution by being suitable for daily use and able to give objective, repeatable data that supports both patient and caregiver with insight, motivation, and better-tailored care.



Figure 44 Current fragmented measurements using VALD dynamometer (VALD, n.d.)

## 7.3 Target Group

The target group was defined based on insights gained from interviews and the intention of the knee sensor sleeve. The interviews gave insight into the different stakeholders involved, although it should be noted that the number of interviews was limited. Combined with the intended use of the product, a target group was defined to identify the kind of stakeholders for whom the product would be most relevant.

### Patients

The primary target group consists of people who have undergone a torn anterior cruciate ligament (ACL) (reconstruction) or knee replacement. This group undergoes a long-term rehabilitation program in which mobility, strength, stability, and confidence in the knee are gradually regained.

During this period, this group often experiences uncertainty about their progress and the right intensity of their exercises. They sometimes lack motivation which affects their therapy adherence. In addition, they want more insight and guidance in and outside of the practice, particularly to prevent overload and keep motivation. They are open to new approaches and technologies that can support their recovery.

### Healthcare providers

The physical therapist is the secondary target group. They are practical and work closely with the patient throughout the entire rehabilitation process. They intensively guide the patient through exercises to build mobility, strength, and balance, and keep adjusting the plan to the progress of the recovery. The physical therapist needs clear, useful information about the patient's progress and wants objective measurements to assess the success of exercises. They are open to new approaches and technologies that help better monitoring the recovery process without adding administrative burden.

Orthopedists are the tertiary target group. From a more medically focused perspective, they monitor recovery at key moments after surgery. They don't want details but concise, clear information about the patient's recovery and performance to identify complications early. They are also open to new approaches and technologies, as long as it does not add additional burden and contributes to better patient care.

# 7.4 Design Goal and requirements

## Design goal

The goal of this design is to develop a textile knee sensor sleeve that can reliably and comfortably measure knee flexion during rehabilitation. The sleeve integrates a strain sensor that gives consistent and reliable data on knee movement. The knee sleeve itself should be comfortable to wear, easy to apply, and intuitive to use, so the patient can monitor their rehabilitation independent and without technical expertise. The built-in electronics are integrated in such a way that they are unobtrusive, safe, and durable, able to withstand daily use without causing discomfort or risk to the user.

The digital environment offers interfaces for the patient, physical therapist, and possibly the orthopedist. Each user receives the information relevant to them in a clear and concise way: realtime monitoring, insights into progress, trends, and any concerns. The focus is on clarity, simplicity, and motivation.

The combination of the knee sleeve and the interface should give insights into progress, support and motivate patients in their recovery process. It should also help healthcare providers collect objective, reliable data to provide the patients with a tailored rehabilitation process inside and outside of practice.

## Design requirements

The requirements were developed using the List of Requirements method from the Delft Design Guide (Van Boeijen et al., 2020) and divided across the various aspects of the concept. The requirements serve as a guideline during the development process and for evaluating the design at the end.

### 1. Functional requirements (sensor)

Nr.	Requirement	Specification	Explanation/clearification
1.1	Knee flexion measurement range	The sensor must be able to measure a knee angle between 0°–140°. In other words, the sensor must still be operational at 50% elongation.	The average range of motion of the knee is between 0° (straight leg) and 140° (full flexion) (Kono et al., 2018). At this angle, the skin is stretched by up to ± 50%. Therefore, the sensor must be effective within this range.
1.2	Sensitivity	The gauge factor must be at least 1.	Above this value, the sensor is sensitive enough to accurately detect small changes in strain.
1.3	Linearity	The linearity must be at least 95%.	Above this value, the sensor response remains sufficiently predictable.
1.4	Hysteresis	The hysteresis may be a maximum of 20%	Although knee return movement is of interest, the primary focus is on maximum flexion; therefore, this value is higher than the other variables.
1.5	Repeatability	The repeatability may not exceed 1%.	Within this value, repeated measurements remain consistent and reliable.
1.6	Skin contact and anatomical fit	The sensor must lie snugly against the skin to follow the anatomy of the knee during flexion and extension without slipping.	Not fitting snugly against the skin causes wrinkles, resulting in unreliable measurements.

Table 7 Functional requirements

1.7	Movement with the knee	The sensor must be securely attached at the top and bottom.	The sensor must be securely attached so that it moves with the knee, ensuring that changes in resistance are measured clearly and reliably.
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### 2. User comfort, ergonomics and appearance (sleeve)

Nr.	Requirement	Specification	Explanation/clearification
2.1	Ease of use	The sleeve must be able to be put on or taken off in <1 minute by a user with limited mobility.	A quick action (<1 minute) prevents frustration, increases ease of use and makes it more realistic that patients can also use the sleeve independently at home.
2.2	Comfort duration	The sleeve should remain comfortable for at least 1 hour of continuous wear when exercising without irritation, pinching or pressure points.	On average, physiotherapy sessions last 30-60 minutes. Therefore, the knee sleeve should be comfortable for at least one hour.
2.3	Range of motion comfort	The sleeve must not noticeably restrict the movement of the knee, including deep flexion and full extension.	Restrictions in flexion or extension can hinder the performance of exercises.
2.4	Lightweight design	The sleeve must be lightweight so that wearing it does not hinder activities or exercises.	A knee sleeve that is too heavy or massive increases the load on the leg.

2.5	Soft and skin-friendly inner surface	The inner surface of the sleeve must be made of soft, skin-friendly materials that prevent chafing or irritation during movement.	The repetitive movement during exercises can cause friction. A soft inner layer prevents skin irritation or chafing.
2.6	No sharp or pointy components	The sleeve must not contain any sharp or pointy components that could cause discomfort, pressure points, or injury.	A fully flexible and flat finished exterior increases comfort and prevents risks.
2.7	Breathability and Moisture Management	The sleeve must be breathable and capable of regulating moisture to minimize heat buildup and perspiration.	Heat and sweat can build up around the knee joint during exercise.
2.8	Stable fit	The sleeve should not shift during activities or exercises.	The sleeve slipping down can cause extra friction.
2.9	Donning guidance	The sleeve must include visible markers or orientation indicators, to show how the sleeve should be put on correctly.	The visible markers must indicate at a glance how it should be worn. Incorrectly wearing affects the measurements.
2.10	Fitting appearance	The sleeve should have a neutral appearance with a colour/design touch	This preference emerged from a discussion in chapter 10.2. Aesthetics

Table 8 User comfort, ergonomics and appearance (sleeve) requirements

### 3. Technical and electronic requirements

Nr.	Requirement	Specification	Explanation/clearification
3.1	Battery life	The battery should last at least 1 hour of continuous use. Preferably longer for multiple sessions.	Since practice sessions last a maximum of one hour, the battery must be able to support at least this amount of use. Preferably longer so it does not need to be recharged after every session.
3.2	Standardisation & safety	Electrical components and conductive yarns should be standardised and certified, ensuring safety and scalability.	Scalability is important for bringing the product to market in the future. The use of standardized components and materials increases the safety of the product. However, the composition that will be created in-house must still be checked by a safety expert.
3.3	Compact electronics	The electronics must be compact and lightweight so it doesn't disturb the user during movement.	The electronics must be small, light and compact so they are not noticed during movement or exposed to snagging and bumping.
3.4	Secure mounting	The electronic components must be securely attached and protected so they cannot shift, detach, or get damaged.	Since the knee sleeve moves a lot, electronics and wiring must not get loose or shift. This prevents malfunctions, wire breakage, and discomfort for the user.

Table 9. Technical and electronic requirements

3.5	Electronics protection	All electronic components must be protected with suitable encapsulation to prevent damage.	When bending the knee, they should be barely noticeable. The protrusion of the components can cause snagging or bumping, which influences both comfort and safety.
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### 4. User Interface requirements

Nr.	Requirement	Specification	Explanation/clearification
4.1	Multi-Interface system	The system must provide two distinct user interfaces: a real-time interface and progress-overview interface for patients, and a clinical dashboard for healthcare providers.	Patients and HC providers have different information needs. Patients need immediate feedback during exercise, while healthcare providers mainly want to see trends and progress over time.
4.2	Clear and simple navigation	All interfaces must provide intuitive navigation with minimal steps required to access key information.	Both patients (who may be experiencing pain, stress, or limited mobility) and healthcare providers (who have limited time) need to be able to find desired information quickly.
4.3	Low cognitive load	The real-time interface must avoid complex metrics and present only helpful information during exercises.	Patients should concentrate on their movements and not be distracted by complex graphs.

Table 10. User Interface requirements

### 5. Sustainability and maintenance requirements

Nr.	Requirement	Specification	Explanation/clearification
5.1	Replaceable components	Sensor and electronics must be removable and replaceable without requiring full reconstruction of the sleeve.	This prevents the entire knee sleeve needing to be discarded if one component is defect.

Table 11. Sustainability and maintenance requirements

# TAKEAWAYS & IMPLEMENTATION

Key takeaways	Implementation
<p><b>Patient journey</b></p> <ul style="list-style-type: none"> <li>The rehabilitation process is long, complex, and full of uncertainties. The emotional journey of patients changes from phase to phase: doubt, frustration, hope, confidence.</li> <li>Monitoring is currently mainly done visually and via objective snapshots. As a result, both patients and healthcare providers lack a continuous overview of progress.</li> </ul>	<ul style="list-style-type: none"> <li>The biggest uncertainties are: Am I making progress? Am I doing the exercises correctly? Am I not overdoing it?</li> <li>The sensor sleeve can have a role in every phase: from baseline measurement before surgery to prevention when returning to sports.</li> <li>The most important design impact is reducing uncertainty and increasing motivation through objective data.</li> </ul> <p>→</p> <p>The patient journey serves as the guiding principle within the project: the sensor sleeve's features should address the pain points along the journey as much as possible. Patient experiences have been incorporated into the list of requirements.</p>
<p><b>Design scope</b></p> <ul style="list-style-type: none"> <li>The project balances feasibility and detail: not a complete product, but a well-functioning prototype solution.</li> <li>The emphasis is on: reliable movement measurement, repeatability, and visualization.</li> </ul>	<ul style="list-style-type: none"> <li>No complete app development, no washability test, no certification, no complex motion capture.</li> <li>The scope focuses on what is essential to test the concept: sensor reliability, wearing comfort, positioning, data visualizations, and usability.</li> </ul> <p>→</p> <p>To ensure the project remains feasible within its timeframe, only those aspects within the scope will be addressed. This also allows to delve into the most important aspects and develop them thoroughly.</p>
<p><b>Problem definition</b></p> <ul style="list-style-type: none"> <li>Rehabilitation lacks continuous, objective insight into progress.</li> <li>Patients often have no insight into their recovery rate and may therefore experience uncertainty and lack of motivation.</li> <li>Physical therapists and orthopedists lack data between consultations and must rely on subjective observations.</li> </ul>	<ul style="list-style-type: none"> <li>IMUs and high-tech systems are complex, relatively expensive, and unsuitable for everyday contexts.</li> <li>There is a clear need for a practical, comfortable, simple, and affordable measurement system.</li> </ul> <p>→</p> <p>The problem must be translated into the design: Simplicity over complexity, focus on daily use, continuous measurement and quick interpretation. The problem definition was incorporated into the development of the LoR.</p>
<p><b>Target group</b></p> <ul style="list-style-type: none"> <li>The patient that wants clarity, motivation, and insight into their progress through movement measurement, trends, and comparison with previous weeks.</li> </ul>	<ul style="list-style-type: none"> <li>The physical therapist that wants clear, useful information about the patient's progress and wants objective measurements to assess the success of exercises.</li> <li>Orthopedists who are interested in overviews of recovery rates.</li> </ul> <p>→</p> <p>The app will have two user modes tailored to each stakeholder:</p> <ul style="list-style-type: none"> <li>Patient: real-time feedback, trends, progress overviews, and motivating elements.</li> <li>Physical therapist: session summaries and progress overviews.</li> </ul> <p>Because of the lower involvement and interest in detail of orthopedists, a separate interface will not be created for this stakeholder. This choice is further explained in 12.8 User Interfaces.</p>
<p><b>Design requirements</b></p> <ul style="list-style-type: none"> <li>Goal: A reliable, comfortable, intuitive sensor sleeve for movement monitoring to reduce uncertainties and increase motivation.</li> <li>The requirements cover: functionality, comfort, electronics, UI, and durability.</li> </ul>	<ul style="list-style-type: none"> <li>The sensor should give reliable and repeatable measurement.</li> <li>The data must be understandable for every type of user.</li> <li>The sleeve must be technically robust yet comfortable and unnoticeable.</li> </ul> <p>→</p> <p>All design decisions are assessed against the requirements list.</p> <ul style="list-style-type: none"> <li>Technical requirements will be assessed through measurements and physical tests.</li> <li>Comfort and intuitiveness will be tested through fit testing, user feedback, and movement testing.</li> </ul>

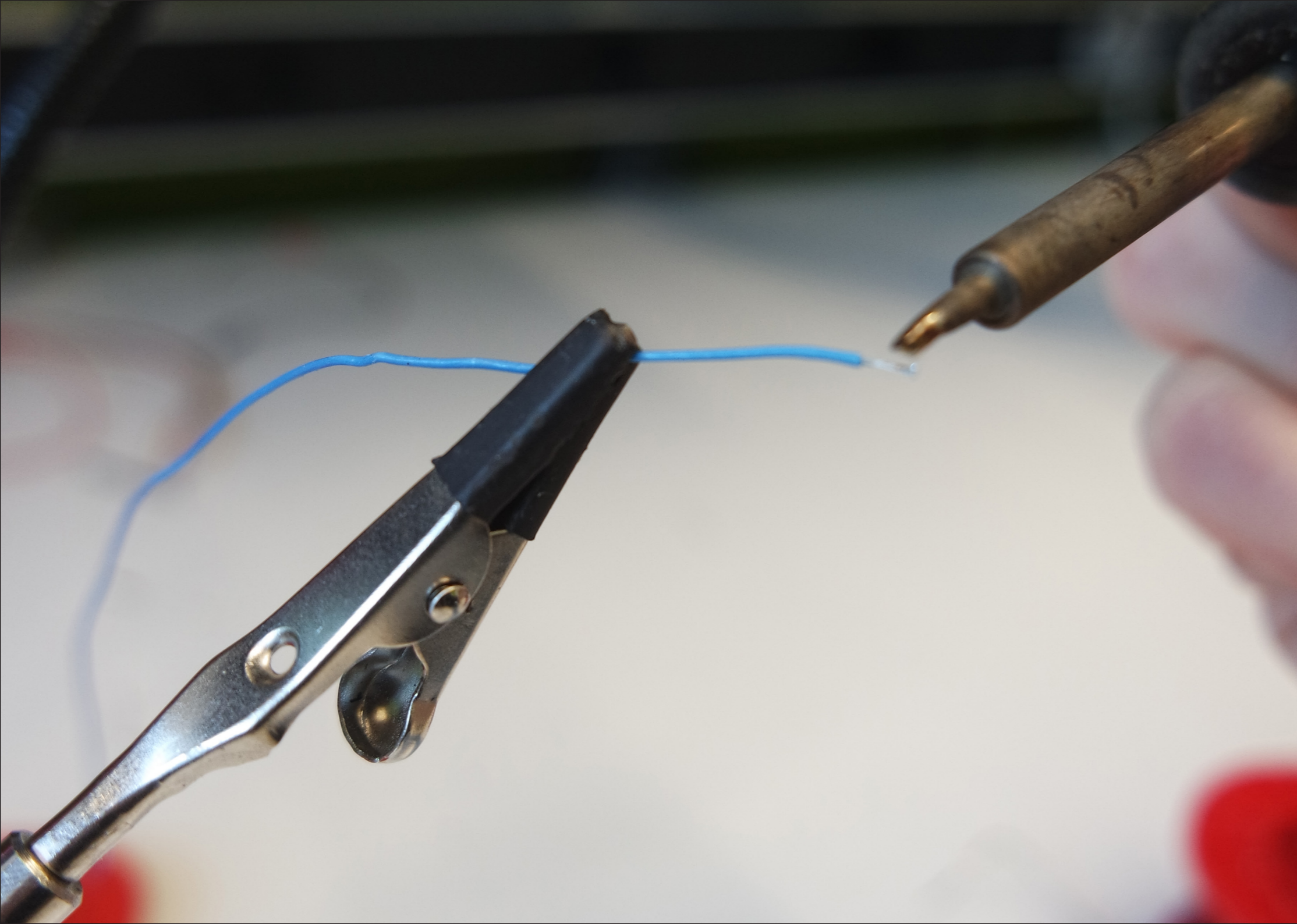


Figure 45. A snapshot of the production process where the electronics are attached using soldering

## PHASE 3

# DEVELOP

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This phase focuses on integrating the sensor into a knee sleeve and further developing the sleeve by investigating its use on the knee and selecting solutions for functional limitations or design challenges. An appearance is also chosen, and research is conducted on how the raw sensor data can be translated into meaningful insights for the user.

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- 8. Sensor integration
- 9. Electronics integration
- 9. The sleeve's appearance
- 10. The user interface



Figure 46. The sensor integrated (stitched) in the fabric

## 8. Sensor integration

In this chapter, the optimal placement of the sensor within the knee sleeve is examined, as well as the effects of the sleeve slipping and how this can be prevented.

- 8.1 Sensor location
- 8.2 Sensor displacement
- 8.3 Anti-shift methods

### 8.1 Sensor location

#### Separate sensor vs integrated sensor

##### Prototype 1: Separate sensor

For the first prototype, a separate stretch sensor was attached to the textile knee sleeve. This prototype aimed to evaluate the initial performance of the sensor and its interaction with the wearer.

##### Insights from the test

The knee sleeve itself forms well to the anatomical shape of the knee due to the compression of the textile. However, the sensor, which is attached as a separate piece to the sleeve, does not move well with the fabric and is not sufficiently tight, resulting in inaccurate measurements (figure 47). In addition, the pattern of conductive yarns used in the sensor increases its stiffness compared to the rest of the knee sleeve. As a result, more force is needed to stretch the area with the sensor than the textile of the sleeve. This difference in elasticity causes that the sensor does not move smoothly with the knee sleeve and does not track the movement of the knee during flexion and extension well.

When the knee sleeve was reversed so that the sensor was positioned on the inside, the sensor seemed to function better during knee flexion. However, during extension, the sensor folded, again resulting in unreliable measurements.

The idea of attaching the sensor separately seemed practical, looking at replaceability in case of failure. However, this test showed that this method is not suitable for accurate and consistent measurements.



Figure 47. Four yarn rows are stitched onto a separate piece of fabric and stitched onto the sleeve



Figure 48. Two yarn rows are stitched directly onto the sleeve

### Prototype 2: Sensor integrated

Based on the insights from prototype 1, prototype 2 integrates the sensor into the knee sleeve. This allows the sensor to follow the anatomy of the knee, fit snugly, and move smoothly with the knee.

### Location sensor

When designing the fabric around the kneecap, the conductive yarn can be placed on the inside or outside of the sleeve. Both options have advantages and disadvantages:

	Conductive yarn on the inside	Conductive yarn on the outside
+	Less chance of damage because the yarn is protected against external factors like snagging on objects or friction with trousers.	Less direct contact with the skin, which increases wearing comfort.  Less exposure to moisture from the knee.
-	Friction with the skin can be slightly uncomfortable. Bigger exposure to moisture (sweat), which affects conductivity.	Bigger risk of damage from external forces, such as friction with clothing or snagging on objects.

Table 12. Yarn positioning evaluation

Damage caused by external forces, like friction with clothing or snagging on objects, can be reduced by adding a thin protective layer over the yarn. This protects the yarn without affecting the comfort or functionality of the sensor. The water test showed that exposure to moisture (sweat), affects the sensor's performance. Therefore, placing the conductive yarn on the outside is the best choice for this application.

## 8.2 Sensor displacement

### Influence of shift

Although prototype 2 appears to remain in place well at first glance, it shifts slightly as the knee repeatedly bends. This causes wrinkles in the fabric when the knee is extended again after a few bending and stretching cycles. Tests show that this significantly impacts the measurement results, as can be seen in the graphs on the right (Figure 50, 51).

The top graph shows the measurements when the sensor sleeve was held in place manually. This shows that the measurement are fairly consistent, varying between 95 and 145 ohms.

The bottom graph shows the situation when the sleeve was not held manually and therefore slowly slid down (Figure 49, 51). The resulting wrinkles affect the measurements because they impact the measured resistance. When the sensor is folded onto itself, the resistance decreases because the number of paths the current can flow through increases.

The bottom graph shows that the measurements vary significantly during repeated bending, reducing the reliability of the data.



Figure 49. The sleeve has slipped causing the sensor to fold

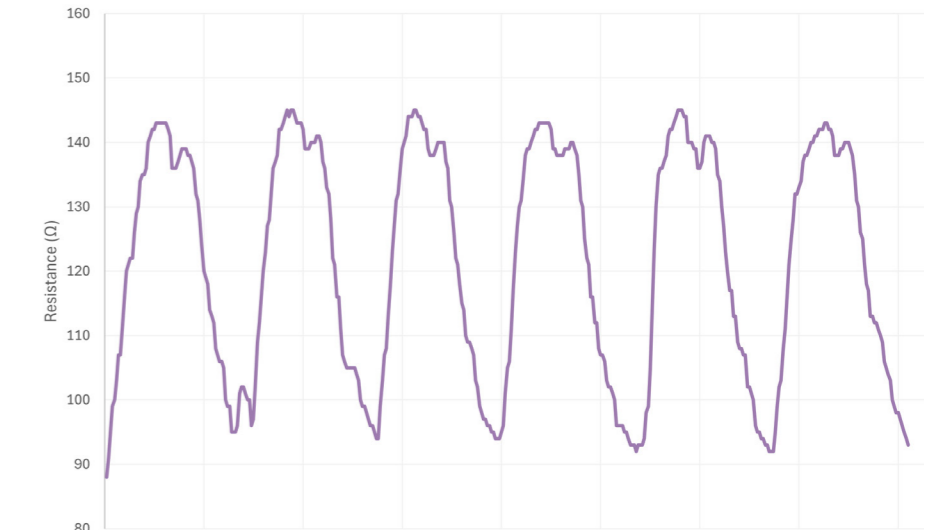


Figure 50. Performance of the sensor when kept in place

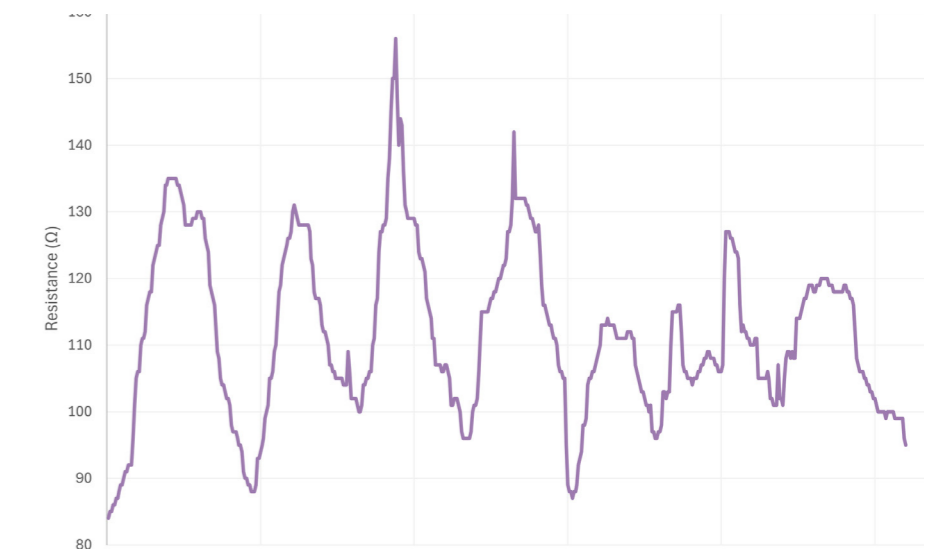


Figure 51. Performance of the sensor when the sleeve slips down

## Influence of placement

To investigate the influence of sensor placement on the measurement results, tests were conducted with the sensor placed in five different positions around the knee:

- On top of the kneecap
- To the right of the kneecap
- On the side of the kneecap
- Next to the kneecap
- On the side of the knee

The results of these measurements are shown as graphs in figure 52.

The sensors placed directly on or on the side of the kneecap show less variation than expected. Although small differences in consistency and absolute resistance values are visible, the measurements are largely consistent with those of the sensor placed on top of the kneecap. Although should be noted that the graph 3 shows higher peak and trough values.

In contrast, a clear difference is observed when placed next to the kneecap and on the side of the knee. Although knee flexion is still registered and reflected in the measurements, the measured change in resistance is much smaller than when placed on the kneecap.

From this, it can be concluded that the exact position of the sensor is not critical, as long as it is placed on or directly around the kneecap. However, locating the sensor on top of the kneecap is the most stable, as there is less shifting there during movement. Placing it on the side of the kneecap causes a bigger risk of shifting due to the movement of the skin around the kneecap.

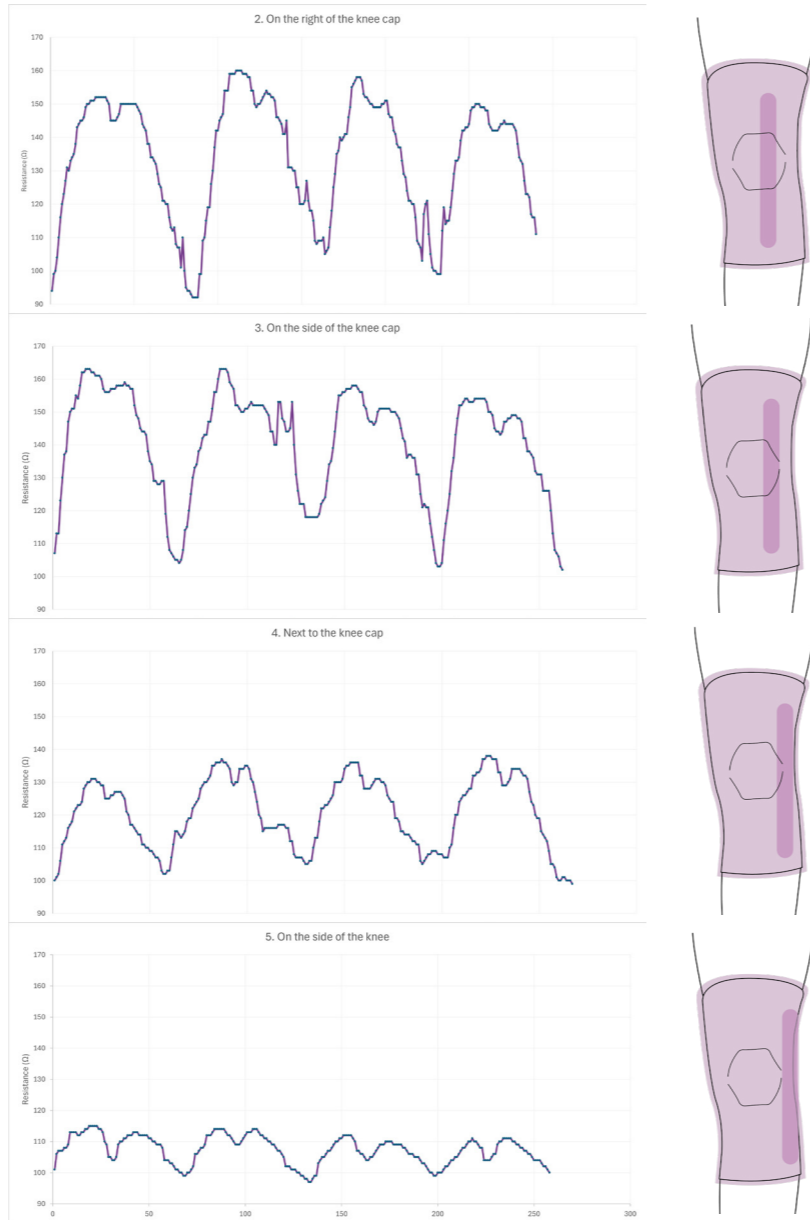
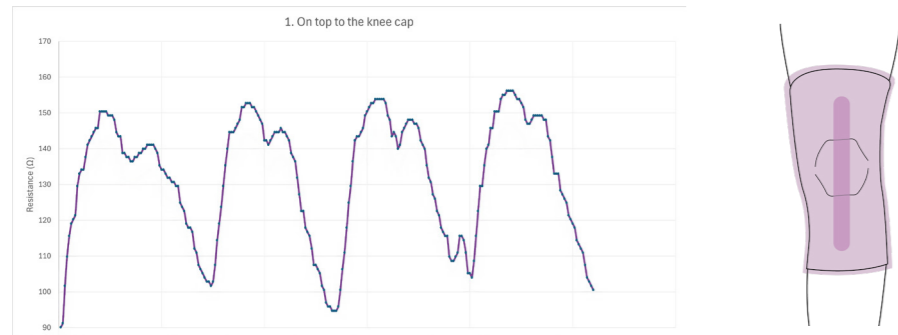


Figure 52. Performance of the sensor when located at varying positions

## 8.3 Anti-shift methods

The previous chapter has shown that slippage of the knee sleeve has a significant impact on the measurements. This must therefore be prevented as much as possible. Figure 54 visualizes various ways of preventing slippage. These were inspired by research into existing braces and ideation sessions. The different methods were assessed using weighted objectives for anti-shift, ease of use, and comfort (Figure 53, Table 13).

Since anti-shifting of the knee sleeve is the most important factor here, it has the highest weighting, comfort is second because it is important in the long term, and ease of use comes last. Each criteria is scored on a scale of 1 to 5. See the assessment and scores on the next page (Figure 53).



Figure 53. Three of the tested anti-shift options

Based on the weighted objectives, it can be concluded that method 1 works best in this case. The elastic in combination with the non-slip material ensures that the sensor stays in place and does not shift or fold. While comfort is high, putting on the knee sleeve can be a little difficult because of the non-slip material. However, when folding the edges outward, with the anti-slip layer facing the outside, allows the sleeve to be put on smoothly.

Method 4 did not have much influence on the shifting of the knee sleeve, but it does ensure that the ends of the sleeve fit nicely on the leg. Since this method has no negative impact on comfort and ease of use, it will also be included in the design for this reason.

Method 1			
Criteria	Weight	Score	Weighted score
Antishift	5	5	25
Comfort	3	4	12
Ease of use	2	3	6
Total			34

Method 2			
Criteria	Weight	Score	Weighted score
Antishift	5	3	15
Comfort	3	2	6
Ease of use	2	2	4
Total			26

Method 3			
Criteria	Weight	Score	Weighted score
Antishift	5	2	10
Comfort	3	5	15
Ease of use	2	5	10
Total			35

Method 4			
Criteria	Weight	Score	Weighted score
Antishift	5	1	5
Comfort	3	5	15
Ease of use	2	5	10

Method 5			
Criteria	Weight	Score	Weighted score
Antishift	5	3	15
Comfort	3	4	12
Ease of use	2	4	8
Total			35

Method 6			
Criteria	Weight	Score	Weighted score
Antishift	5	3	15
Comfort	3	2	6
Ease of use	2	2	4
Total			26

Method 7			
Criteria	Weight	Score	Weighted score
Antishift	5	1	5
Comfort	3	3	9
Ease of use	2	4	8
Total			24

Table 13. Weighted objectives of 7 anti-shift methods

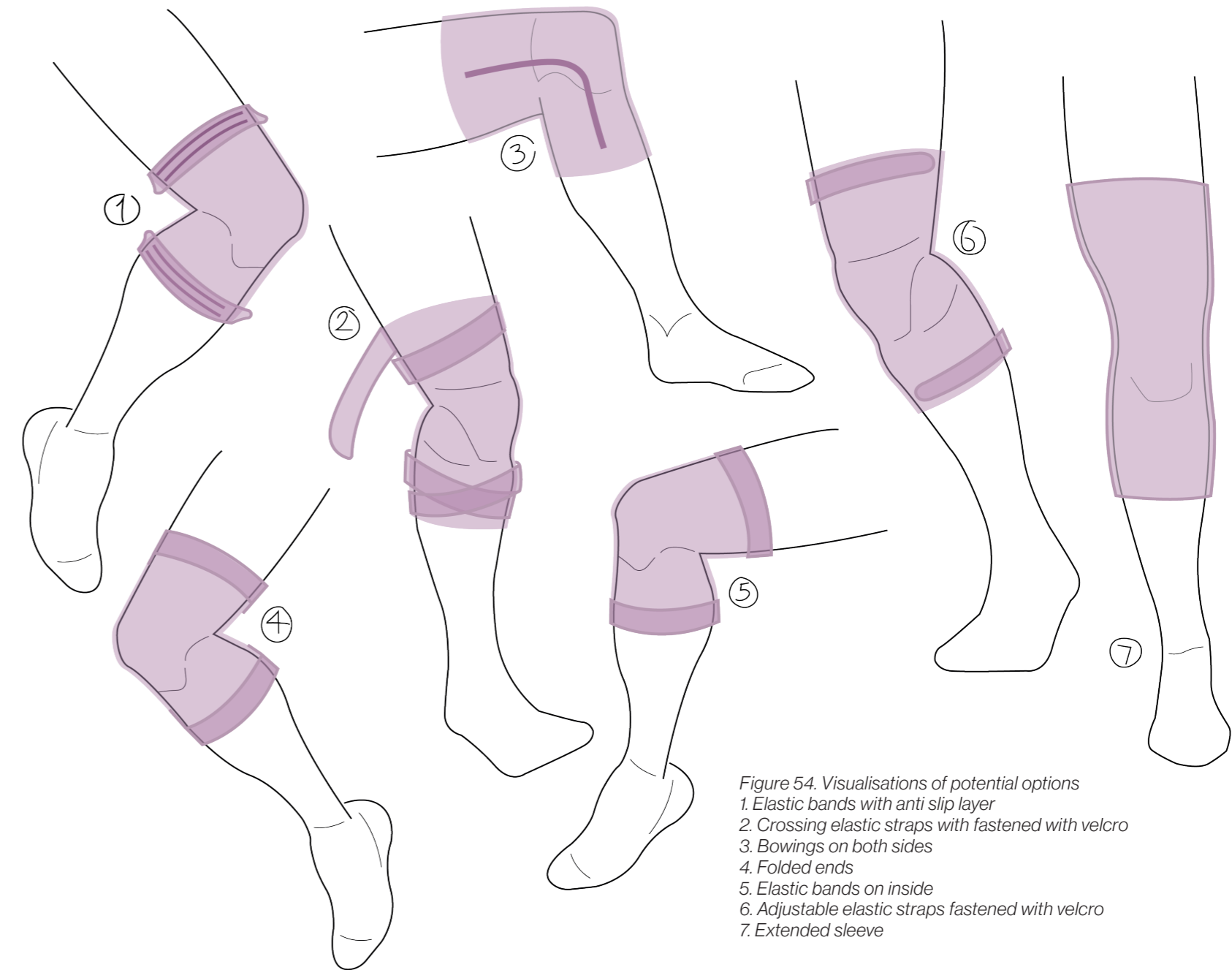


Figure 54. Visualisations of potential options  
 1. Elastic bands with anti slip layer  
 2. Crossing elastic straps with fastened with velcro  
 3. Bowings on both sides  
 4. Folded ends  
 5. Elastic bands on inside  
 6. Adjustable elastic straps fastened with velcro  
 7. Extended sleeve

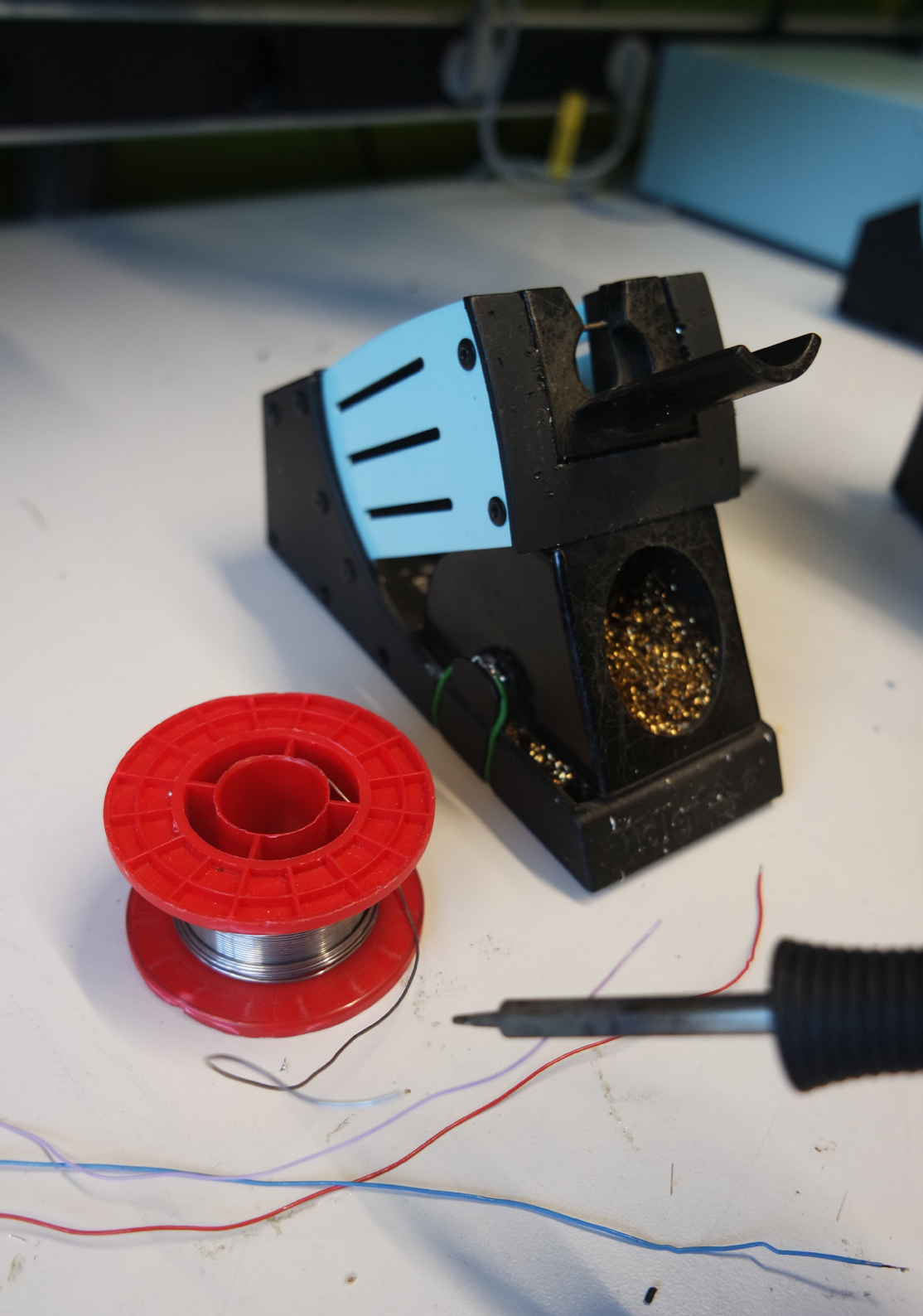


Figure 55. A snapshot of the production process of the electronics part

## 9. Electronics integration

This chapter investigates the optimal integration location of the electronics, the selection of suitable protective materials, and the options for the electronics connecting to the sensor.

- 9.1 Location electronics
- 9.2 Electronics protection
- 9.3 Sensor connection

### 9.1 Location electronics

The battery and seeeduino XIAO form the main part of the electronics within this concept. To ensure that these do not negatively impact comfort, the placement of these components was investigated in three locations (Figure 56). Placing the electronics on the inside of the leg was ruled out because of friction with the other leg. The location was discussed with three participants, and based on these discussions, the Harris profiles below were created, showing the resulting scores.

Location 1	Location 2	Location 3
-- - + ++	-- - + ++	-- - + ++
Comfort	Comfort	Comfort
Stability	Stability	Stability

Table 14. Electronics locations evaluation

Placing the electronics on the front of the leg (location 3) is the least successful option. At this location, bending the knee causes the electronics to move. This not only affects comfort but also stability. The electronics can also be uncomfortable when sitting with both legs crossed.

Locations 1 and 2 are both good options. However, location 1 is placed on the thigh, which is a larger surface area and therefore slightly less noticeable, making it the preferred option.

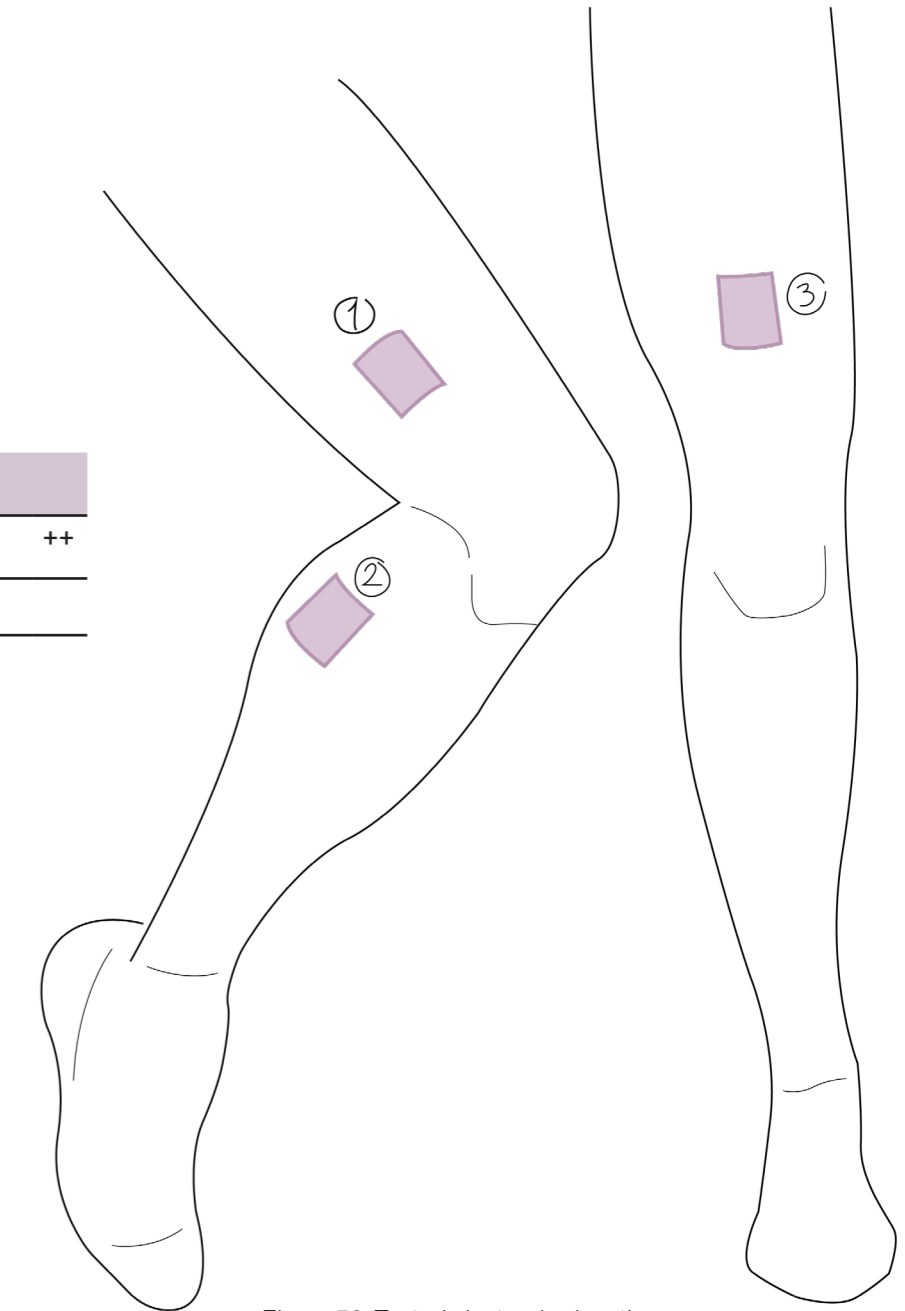


Figure 56. Tested electronics locations

## 9.2 Electronics protection

The concept uses a Seeeduno XIAO nRF52840 and 500mAh battery. This microcontroller was chosen because it is compact, supports Bluetooth Low Energy (BLE) for wireless data transmission, and has no unnecessary features. This 500 mAh battery was chosen because it lasts around 8 hours, which covers eight one-hour sessions without the need for frequent charging. A smaller, more energy-efficient battery could be implemented later which is further discussed in the Recommendations.

It is important that the electronics are well protected. Impacts or point loads can damage the components, which may cause system failure and creates risks to the user. The battery must also be protected against puncture, because this can lead to leakage, short circuiting, or even fire, which affects both the device's operation and user safety. Several options were considered to select a suitable protection solution for the electronics.

### Hard casings

Several combinations are possible for placing the electronics: the components can be stacked (option 1), placed above each other (option 2), or placed side by side (option 3) (Figure 57).

To ensure stability and comfort, it is investigated whether (part of) the electronics should be placed in a hard casing.

To determine the most suitable configuration, the various casings were tested by placing them in a pouch on the outside of the thigh. Although the casings were not clearly noticeable, a hard plastic casing made the electronics bulky and rigid. Especially with option 1, the extra thickness made the electronics more sensitive to bumps. This led to the question whether a hard casing is necessary for sufficient protection.

### Soft housing

Therefore, additional research has been done into alternative, flexible, protective materials that offer both impact protection and comfort during movement.

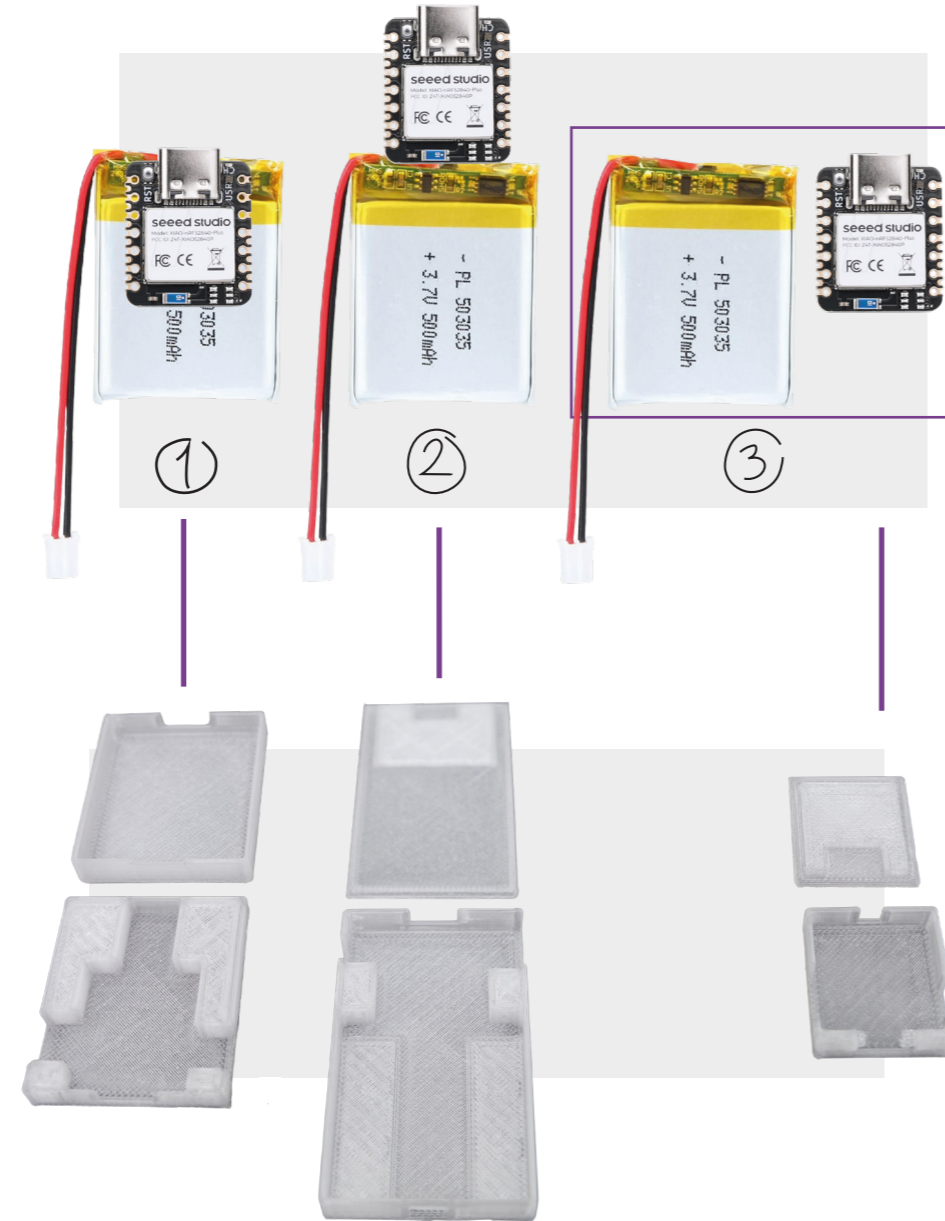


Figure 57. Electronics compositions options and the 3D casings

When protecting the electronics in a knee sleeve, it is important that the material not only withstands impact but is also flexible enough to follow the form of the leg. A material that is too stiff can reduce comfort.

Various materials have been investigated, including neoprene, foam, flexible plastics, and leather (Figure 58). The properties of the materials were investigated by colliding them and the electronics with hard and pointy objects. These tests showed that neoprene and foam materials offer good shock absorption and flexibility, but do not give enough protection against sharp or point impact and can lose their shape over time. Flexible plastics, on the other hand, offer good protection against pointy impacts but offer less effective shock absorption.

Leather offers a unique combination of properties: it is strong, durable, and provides good impact protection. At the same time, it offers enough flexibility to form to the shape of the leg. In addition, leather keeps its shape and strength over time and feels comfortable on the body. This balance between protection, flexibility and comfort led to (imitation) leather being chosen as the most suitable material for protecting the electronics in the knee sleeve.

The electronics are housed in a leather pouch (Figure 58). This ensures they are unnoticeable on the leg, and the pouch gives protection both inside and outside against impacts and point loads.

If a reliable connection can be developed in the future that allows the electronics to be removed, the entire pouch can be easily detached. This allows all the electronics to be taken out of the knee sleeve at once, making the sleeve easy to wash.

An additional method is to first encase the electronics in a layer of flexible silicone, which gives extra protection against impacts, pressure, moisture, and dust while keeping the knee sleeve flexible. This silicone-encased part is then placed inside the leather pouch, ensuring the electronics are fully protected and easily removable.

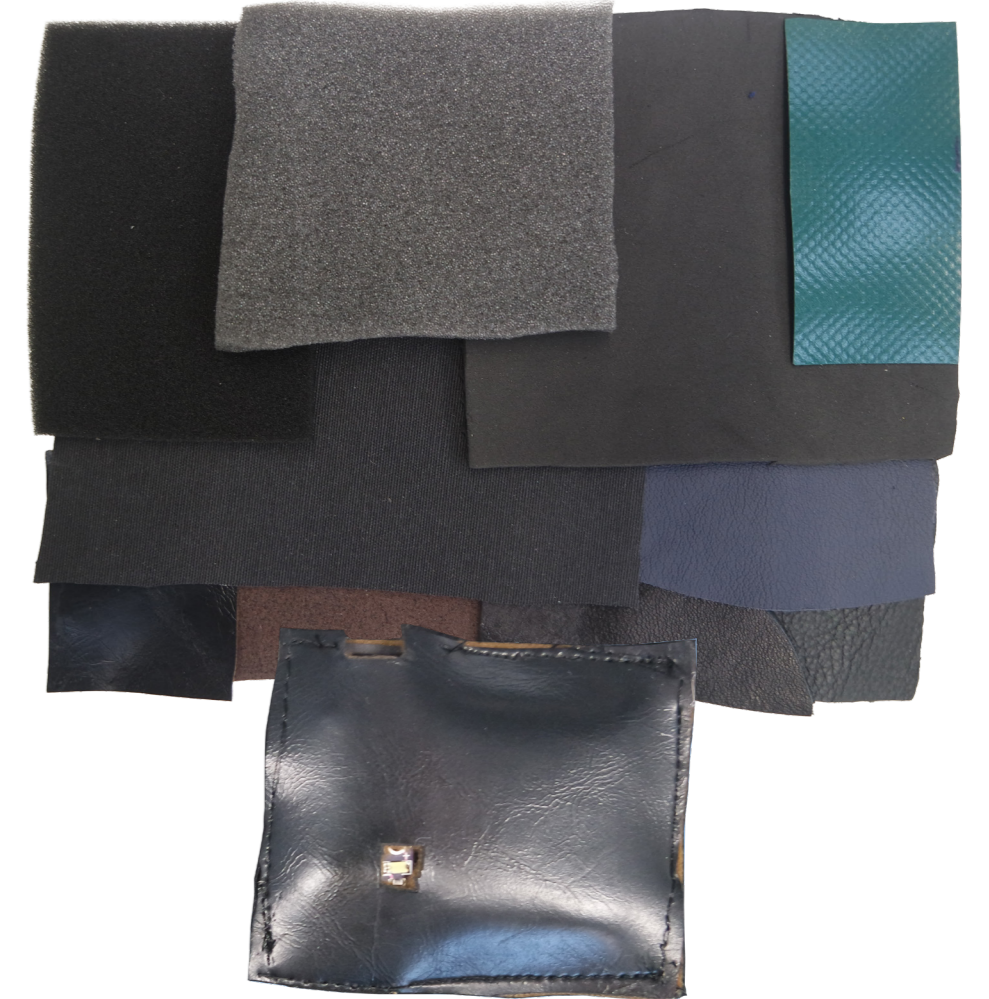


Figure 58. Investigated materials and the the selected protection pouch



Figure 59. Possible smart textiles connection options

## 9.3 Sensor connection

### Connection between yarns and rigid electronics

One of the most challenging but most important connections within e-textile systems is that between conductive yarns integrated into textiles and rigid electronic components, in this case the seeeduino XIAO. Conductive yarns used in wearable sensors usually consist of silver-coated polymers or stainless steel filaments. These materials are not suitable for direct soldering: the high temperatures used for soldering leads to thermal degradation of the fibers and can scorch the yarn or damage the conductive coating. This results in an unreliable or even failing connection.

For this reason, conductive yarns must be connected to the seeeduino XIAO in an alternative way. In addition, there are more constraints; the connection is located in a wearable system that is repeatedly bend and moved while positioned and worn. Therefore, strain relief is important to limit stress on the electrical connection. To further minimize the influence of stretch on the connection, it is positioned on a non-stretchable textile part.

### Alternative connection options

A frequently mentioned alternative to soldering in e-textiles is the use of conductive adhesives (Stanley et al., 2021). This method most closely resembles soldering because, like soldering, a permanent electrical connection is created between two conductive elements, but without high temperatures. This makes conductive adhesives useful for non-solderable materials like conductive yarns. However, conductive adhesives in general have a lower conductivity than soldered connections and are sensitive to aging, moisture and temperature cycles (Zhang et al., 2023)(Acevedo et al., 2025).

Another method is the use of stitched connections, in which conductive yarns are sewn or embroidered directly to a contact point (Figure 59). This technique is useful for textile production and keeps the material flexible and soft. Stitched connections are therefore often used for textile-to-textile interconnects. However, this method is less suitable for connecting rigid electronics, like the Seeeduino XIAO in this case. Stitched connections can also have a variable contact resistance, which depends on the stitch type,

thread tension, and wear (Stanley et al., 2021). On the other hand, more and more electronic components are becoming available that are specifically designed for stitching or integration into fabric (like LEDs and sensors). In addition, mechanical connectors like snaps (Figure 59), velcrofasteners, and pin headers are an option. These can be reliable, withstand up to 5000 attaching cycles, and are detachable. This offers advantages for maintenance and washing (Ugale et al., 2024). However, such connectors are often quite large and rigid, which is a disadvantage for use within the knee sleeve, where the system must be soft, compact, and flexible.

### ShieldIt Super

A more compact, flexible option is ShieldIt Super (Figure 60). ShieldIt Super is a thin, metal-coated fabric that can be permanently applied to textiles by ironing. This creates a flat, low-resistance, and stable contact surface. The sensor's conductive yarns can be stitched to this layer which maintains the flexibility. Electrical wires can be attached by soldering. However, since the material is sensitive to the high temperatures of the soldering iron, direct soldering is unsuitable. Using low-temperature solder paste, which melts at lower temperatures, is a suitable solution. The ShieldIt layer thus forms an electrical transition zone between the textile and the hard electronics.

ShieldIt Super is soft and thin, and can be added unnoticeable in the knee sleeve, which does not negatively impact comfort (Figure 60). The combination of the ShieldIt Super ironed on a non-stretchable underlayer, stitched-on conductive yarns, and a soldered wire connection can be concluded as the best option because of its good balance of electrical reliability, flexibility, and comfort.

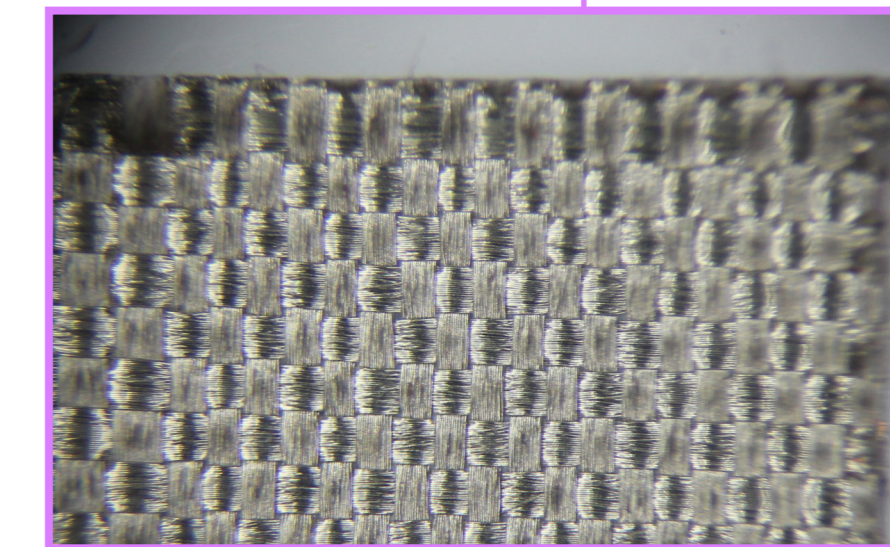
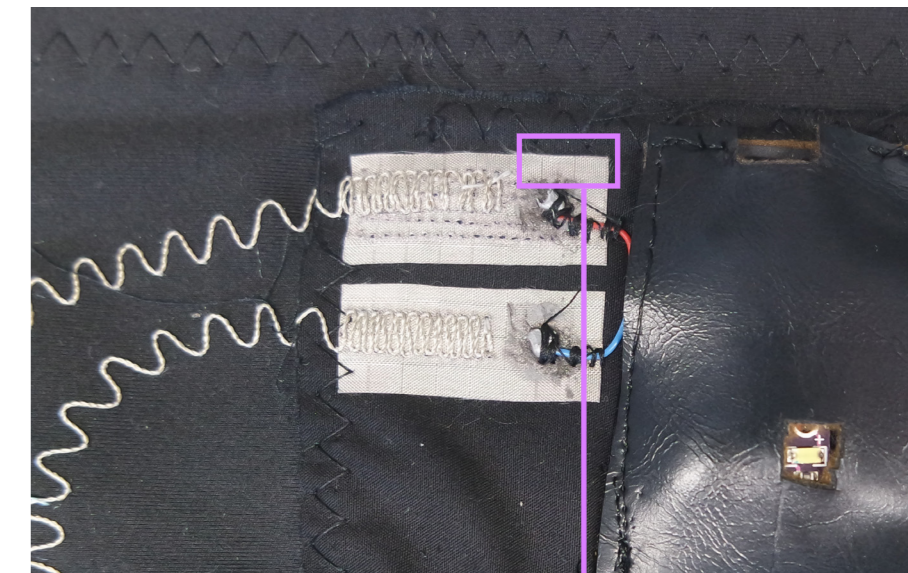


Figure 60. Integration of the ShieldIt material and the material under the microscope; the material consists of a robust rip-stop polyester substrate with a copper-nickel conductive layer, with the woven structure visible under the microscope as a checker-like pattern.



Figure 61. The sleeve's final design

## 10. The sleeve's appearance

This chapter uses user discussions to determine the most effective cues for correct positioning and to develop a desired design.

10.1 Cover layer

10.2 Placement use cues

10.3 Aesthetics

### 10.1 Cover layer

Earlier in the process, the conductive yarns were placed on the outside of the knee sleeve to prevent contact with moisture and skin friction. However, this makes the sensor vulnerable to damage. To prevent this, a protective layer must be added. By extending this layer over the electronics as well, the electronics can be fully integrated into the overall design (Figure 62).

This layer can also be integrated in a smart way into the knee sleeve's design, fulfilling multiple functions:

- Protecting the sensor
- Supporting correct positioning
- Offer an attractive design



Figure 62. The sensor and electronics integrated in the knee sleeve with the purple line indicating the cover layer position

## 10.1 Placement use cues

The placement tests showed that correct sensor positioning is important for gaining reliable measurements. To ensure consistent and repeatable results, it is important that the correct placement of the knee sleeve is directly visible and understandable to the user. To support this, use cues were applied: visual elements on the knee sleeve that help the user position the sleeve correctly.

The kneecap is the most obvious and easily recognizable reference point on the knee. Therefore, this location was chosen as the starting point for both the positioning of the knee sleeve and the associated use cues.

### Tactile use cues

Existing knee braces often use donut-shaped foam/silicone blocks that not only provide support but also help with correct positioning. This solution was tested to gain insight into the advantages and disadvantages of tactile use cues compared to visual cues alone (Right images, figure 63). This test revealed several advantages and disadvantages (Table 15).

+	Incorrect positioning of the donut and knee sleeve is noticeable, because it creates pressure on unintended areas and feels less comfortable. This encourages the user to position the sleeve correctly.	
-	Adding a foam donut reduces the simplicity of the knee sleeve. The stretch sensor allows the brace to remain thin, unobtrusive, and easy to wear, but including the donut affects these qualities.	As mentioned earlier, a recovering knee should be supported as little as possible to regain its natural function. The foam ring gives support that actually want to be avoided.

Table 15. The use of tactile cues evaluation

### Visual cues

Besides tactile cues, clear visual cues can also contribute to correct placement, without the need for additional material or thickening. To determine the most effective visual cues, several visualisations were developed, inspired by existing knee brace designs and resulted from an ideation session. These visualisations were discussed with four participants. During a group discussion, the participants were asked to evaluate the use cue visualisations based on clarity, ease of interpretation, and the ability to immediately indicate correct positioning without additional explanation. The various options were evaluated, with the enlarged visualisation in Figure 63 concluded as the best option.

Based on the evaluation criteria, the combination of a circle and a vertical line was considered the best option by the participants. According to them, the circle gives clear information about the positioning in relation to the kneecap, while the vertical line emphasizes that correct horizontal alignment of the knee sleeve is also important.

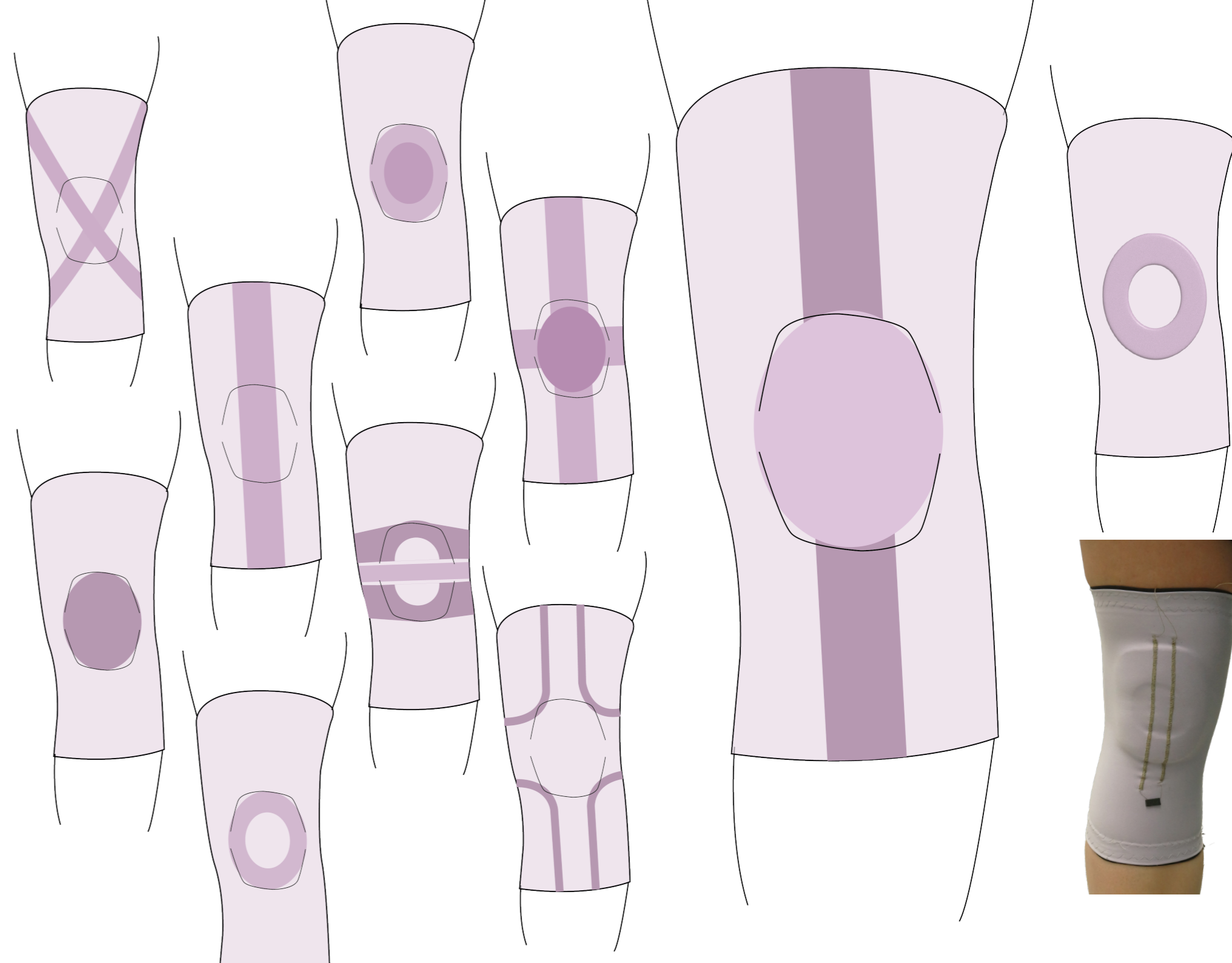


Figure 63. A variety of visual cues to support correct positioning of the sleeve and one tactile cue option

## 10.2 Aesthetics

### Preference research

To determine the appearance and design of the knee sleeve, visual preference research was done with the four participants. The participants were shown images of existing knee braces, divided into three categories: colorful, neutral, and a combination of neutral with a subtle color accent (Figure 64), the whole image frame can be found in appendix C).

All participants considered the colorful knee braces too flashy. Neutral knee braces, particularly in black or dark blue, were described as attractive and acceptable as participants considered them discreet and subtle. Knee sleeves in white or light skin tones, on the other hand, were more often associated with a medical device or a traditional support stocking, which gave a less desirable appearance.

All four participants showed a clear preference for a neutral base with a subtle color or design accent. This combination was considered not too flashy, but visually interesting. In addition, two participants specifically mentioned that this look gives a sporty impression, which is more suitable for rehabilitation exercises. This was seen as positive, as it reduces the product's association with hospital care or the surgery itself.

Based on these insights, a neutral design with a subtle color accent was chosen to create a balance between an neutral appearance and a modern, sporty look.



Figure 64. Existing knee sleeves in three types where shown

### Ideation and final design

The use cues and the sensor protection are located on the outside of the knee sleeve, and thus determining the product's aesthetics at the same time. The design combines protection, use cues, and appearance to integrate multiple functions into a single design.

Protection is needed across the length of the sensor, the path to the electronics, and the electronics housing itself. Previous research revealed which positioning of the use cues was the clearest and most intuitive for the user. This, combined with the necessary protection zones, formed the base for the final design (Figure 65).

Based on this, a design was developed that visualizes the knee sleeve's function while at the same time ensuring a distinctive and recognizable appearance. Figure 66 shows the design including some previous ideation. The goal was to create a unique design that communicates the knee sleeve's unique functionality and in that way contributes to the product's recognizability. The design visually shows that a current is flowing through the knee sleeve, represented by the blue line that runs along the knee to its end point; the electronics. This aligns with the actual operation of the product, where the sensor below changes in resistance. In this way, the functionality of the knee sleeve is subtly reflected in the design. The color blue was chosen because of its clear contrast with the black base colour, without appearing too bright or dominant.

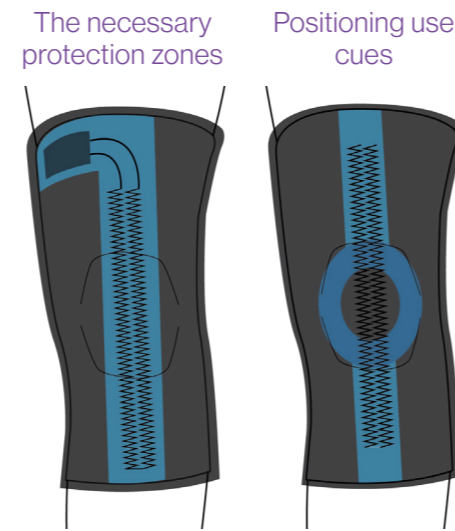
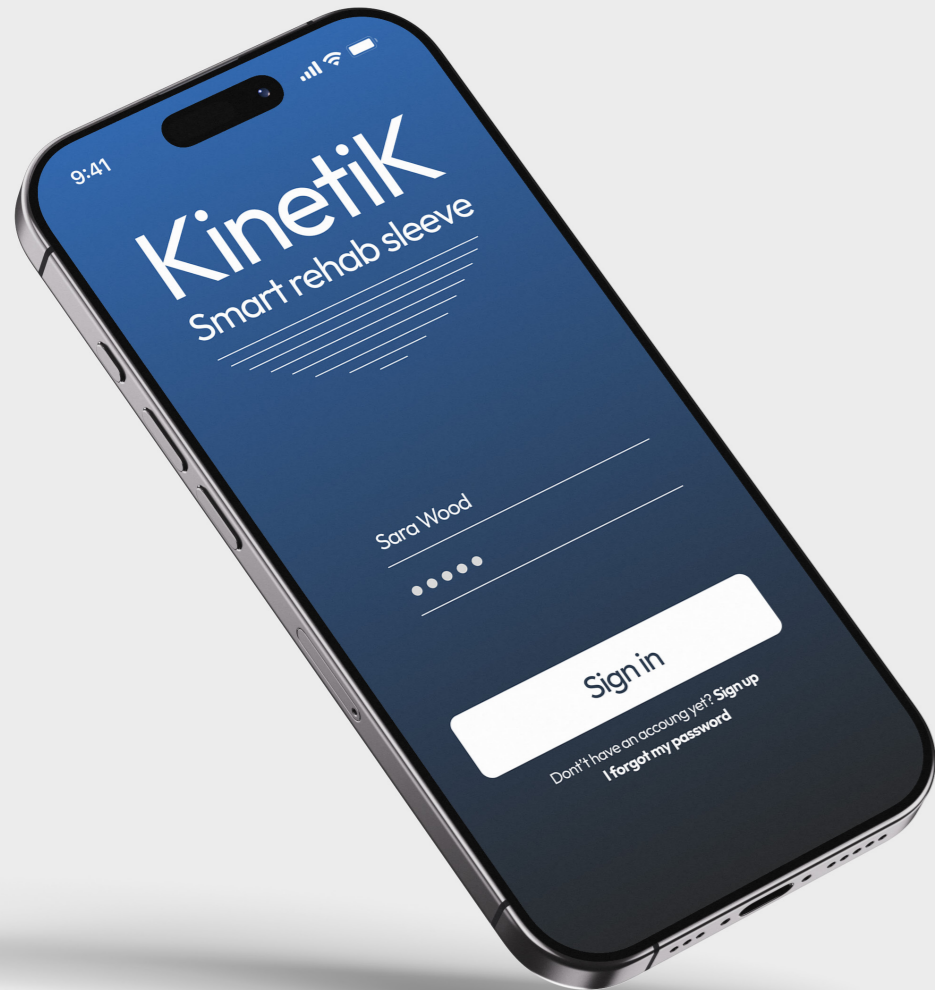


Figure 65. The design of the sleeve was based on a combination of the necessary protection zones and the selected positioning cues



Figure 66. Ideation, final design and stitch exploration

Figure 67. The login page of the User Interface



## 11. The User Interface

This chapter investigates how raw data can be translated into meaningful and engaging insights for the user, and how these insights can best be presented within an app interface.

- 11.1 Gamification
- 11.2 Data representation
- 11.3 Uncertainties to clarify

### 11.1 Gamification

The data needs to be presented to the user in an accessible way to be usable for the patient and the physical therapist using an interface. For this purpose, an interface will be used. To reach the predefined desired outcome of supporting therapy, increase motivation, and keep adherence, it is important to consider how the data is presented. An effective interface can convert complex movement data into understandable feedback, insight into progress, and motivational elements, enabling patients to participate actively in their rehabilitation and allowing healthcare providers to better guide them.

#### Gamification research

Gamification, the use of game elements such as goals, feedback, rewards, and insights into progress in a non-game context, is increasingly being used to improve rehabilitation and therapy compliance. The literature describes how gamification transforms physical activity and rehabilitation exercises into a stimulating and measurable process, thereby increasing patient engagement (Alfieri et al., 2022) (Xu et al., 2022).

Within musculoskeletal rehabilitation, for example in osteoarthritis, fractures, and ligament injuries, studies show that gamified exercise programs are often more effective than traditional forms of exercise. Patients show more motivation, a higher adherence to therapy, and report a more positive perception of their health (Alfieri et al., 2022). Broader research into chronic and musculoskeletal conditions shows that gamification keeps users more active, especially when getting clear guidance and feedback (Alfieri et al., 2022) (Selles et al., 2024). In line with this, personalized gamified systems that adapt exercises and progress to individuals increase engagement and adherence, by tailoring challenges to the patient's current performance (González-González et al., 2019).

Gamified rehabilitation often uses technology, combined with design choices that stimulate motivation. Through continuous and objective monitoring, users receive real-time feedback, insight into progress, and rewards for consistent behavior in a simple and accessible way. These lower the threshold for exercise and contribute to engagement in the rehabilitation process (Alfieri et al., 2022) (Xu et al., 2022).

### Conclusion and design principles

For patients that are recovering from knee surgery, gamification can help with sticking to the rehabilitation program. When exercises and daily movements are presented as a challenge or process with visible progress, they are less likely to be perceived as monotonous or painful therapy. By making rehabilitation transparent and measurable, gamification can contribute to better compliance and more motivation to persevere, which is important for a successful recovery.

Five principles have been established to convert the insights gained from the gamification research into guidelines for the corresponding interface of the knee sensor sleeve (Figure 68).



Figure 68. Five principles converting the research insights into guidelines for the interface of the knee sleeve



## 11.2 Data representation

### Interface structures

As discussed earlier, sports watches continuously collect big amounts of physiological and behavioral data, like heart rate, movement, and sleep. These only become valuable when users can interpret them right and relate them to their own behavior and goals. Not the amount of data, but the way in which this data is visualized determines whether users get meaningful insights, stay motivated, and continue to use the application (Huang, 2022) (Murnane et al., 2020)(Dong et al., 2025).

Sports watch apps like Garmin Connect, Polar Flow, Apple, Suunto App, and Coros App act as a translation layer between complex sensor data and understandable information (Figure 69, 70). Research on cognitive load shows that without thoughtful interface choices, presenting data can lead to confusion, high cognitive load, and misinterpretations (Buchner et al., 2021) (Balasm et al., 2025)(Ihsan et al., 2024). Since these types of interfaces have had years of iteration and user research, they are used as a reference for the design of the knee sleeve interface.

### Screen structure and information

Despite different visual styles, sports watch apps often have similar screen types that align with cognitive goals such as orientation, analysis, and reflection. Dividing information into functional screens reduces cognitive load. Data is chunked and presented selectively so that users only see what is relevant to the current task or context (Balasm et al., 2025)(Dukalski et al., 2025).

The home screen, or dashboard, plays a central role in this. It displays a limited selection of information, like daily activity or the status of recent measurements, so that users can quickly orient themselves. For more insight, users can navigate to screens with more detailed data, like activity overviews, heart rate graphs, or sleep phases. This approach follows the principle of progressive disclosure: information is shown step-by-step when the user actively asks for it (Dukalski et al., 2025)(Balasm et al., 2025).

Figure 69. interface screens of Garmin, Polar and Suunto

### Data representation and visual hierarchy

Instead of displaying raw values, the focus is on trends over time, which are represented using graphs and summaries. Users can better interpret data when they can recognize changes and patterns (Wang et al., 2022).

To design the data, sports watch apps often use color coding, icons, and simple graphs to direct the user's attention and make relevant information recognizable. This visual hierarchy allows users to process information without having to analyze every detail. This reduces the cognitive load (Balasm et al., 2025).

### Conclusion

Based on the literature on sport watch apps, it can be concluded that the focus within a wearable interface should not be on the amount of data, but on how this data is presented and how it will be interpreted (Huang, 2022) (Murnane et al., 2020)(Dong et al., 2025). For the knee sleeve, this means that the home page should have a clear dashboard with a selection of relevant information. More detailed insights should be available via step-by-step navigation.

In addition, it is important to visualize trends and patterns rather than individual values by means of color coding, icons, and clear graphs, so that the user can give meaning to their data without high cognitive load.

Figure 70. An Apple watch and interface combination (Riley, 2019).



## 11.3 Uncertainties to clarity

To create a clear overview of the various steps, touchpoints, and stakeholders within the entire process, a patient journey was created. This patient journey helped identify design opportunities, which determined where the knee sleeve could play a valuable role in the rehabilitation process. This chapter explores how these design opportunities can be translated into concrete functions of the knee sleeve (Table 16).

### Phase 1

Design Opportunity	Information Needed	Needed data	How it provides insight
1.1 Baseline before surgery/injury	Know starting mobility	Maximum and minimum knee angle (range of motion), symmetry	Shows the patient their starting point, making future progress measurable

### Phase 2

Design Opportunity	Information Needed	Needed data	How it provides insight
2.1 Continuous monitoring of improvement	Track gradual gains in movement and exercise quality	Flexion count, maximum knee angle per exercise, intensity, asymmetry and consistency	Visualizes gradual improvements, reducing frustration when progress feels slow
2.2 Support for physical therapists	Understand exercise performance and deviations	Flexion count, maximum knee angle per exercise, intensity, asymmetry and consistency	Helps tailor exercise programs based on objective data rather than subjective observation

Table 16. The design opportunities translated into insights

### Phase 3

Design Opportunity	Information Needed	Needed data	How it provides insight
3.1 Support for evaluation	Identify if progress is slowing or plateauing	Historical data of flexions, intensity, consistency and asymmetry	Facilitates conversations between patient and therapist based on measurable trends
3.2 Real-time feedback	Ensure exercises are performed safely and correctly	Current knee angle, consistency, asymmetry and deviations from safe range	Allows patients to correct movements immediately, reinforcing proper execution and confidence
3.3 Visualization of progress	Make improvement tangible	Graphs of flexions, maximum knee angles over time, asymmetry, intensity and consistency	Makes improvements tangible and supports adherence to rehabilitation
3.4 Insight into current capabilities	Understand current functional capacity	Maximum angle per session, changes over multiple sessions	Provides context to isolated measurements, increasing confidence in recovery

Table 16. The design opportunities translated into insights

### Phase 4

Design Opportunity	Information Needed	Needed data	How it provides insight
4.2 Support for return-to-activity decisions	Assess readiness for more demanding activities	Maximum angle, symmetry and consistency	Provides objective evidence that rehabilitation criteria are met
4.3 Reducing uncertainty	Compare current performance to previous sessions	Comparative graphs of current and previous sessions	Helps patients and clinicians understand if deviations are normal or require attention

Table 16. The design opportunities translated into insights

Within this project, the focus of the user interface will be on the second and third phases of rehabilitation, as these together constitute the largest part of the rehabilitation process. Future projects may further explore establishing a baseline for rehabilitation and giving insight into readiness to return to sport and reinjury prevention.

# TAKEAWAYS & IMPLEMENTATION

Key takeaways	Implementation
<p>Sensor placement and design</p> <ul style="list-style-type: none"> <li>A separate sensor on the knee sleeve result in inaccurate measurements because of bad movement with the fabric and differences in elasticity.</li> <li>Integrating the sensor into the sleeve improves the fit, movement tracking, and measurement reliability.</li> </ul>	<ul style="list-style-type: none"> <li>Placing conductive yarn on the outside reduces moisture degradation and rubbing against the skin</li> </ul> <p>→</p> <ul style="list-style-type: none"> <li>The sensor will be integrated into the textile of the sleeve.</li> <li>The yarn will be located on the exterior. A protective layer will be added to prevent snagging or friction damage.</li> </ul>
<p>Sensor displacement and anti-shift</p> <ul style="list-style-type: none"> <li>Integrated sensors shift slightly during repeated knee movement, which affects measurement accuracy.</li> <li>The sensor needs to be positioned on top of the kneecap to give stable and the most accurate results.</li> </ul>	<ul style="list-style-type: none"> <li>Elastic bands with non-slip material offers the best combination of shift prevention, comfort and ease of use.</li> </ul> <p>→</p> <ul style="list-style-type: none"> <li>Elastic non-slip material will be added at the top and bottom of the sleeve to minimize shift.</li> <li>Visual/tactile cues will be integrated in the design of the sleeve to guide proper positioning.</li> </ul>
<p>Electronics placement and protection</p> <ul style="list-style-type: none"> <li>The best location for the electronics is on the thigh for highest comfort and minimal interference with movement.</li> <li>The protection material should offer impact resistance, flexibility, and comfort.</li> </ul>	<ul style="list-style-type: none"> <li>A leather pouch with possible silicone padding gives reliable protection while offering flexibility.</li> </ul> <p>→</p> <ul style="list-style-type: none"> <li>The electronics will be added on the upper thigh.</li> <li>The electronics will be encased in a leather pouch for impact protection while maintaining comfort.</li> </ul>
<p>Sensor-to-electronics connection</p> <ul style="list-style-type: none"> <li>Direct soldering of conductive yarn is unsuitable; alternative connections are needed.</li> </ul>	<ul style="list-style-type: none"> <li>ShieldIt Super combined with stitching and low-temperature soldering provides a flexible, reliable, and compact textile-to-electronics interface.</li> </ul> <p>→</p> <ul style="list-style-type: none"> <li>ShieldIt Super will be used as an interface between the yarn and electronics.</li> </ul>
<p>Use cues and aesthetics</p> <ul style="list-style-type: none"> <li>Clear visual and tactile cues ensure correct sensor positioning, with the kneecap as the primary reference.</li> <li>Neutral base colors with subtle accents were preferred for a modern, sporty, and discreet appearance.</li> </ul>	<ul style="list-style-type: none"> <li>The design needs to be a combination of a sensor protection, use cues and visual indicators of functionality into a cohesive desired aesthetic.</li> </ul> <p>→</p> <ul style="list-style-type: none"> <li>The final design will be integrated in the sleeve by embroidering the pattern on a separate piece of fabric which will be added as a extra layer on the sleeve.</li> </ul>
<p>Gamification and data visualization</p> <ul style="list-style-type: none"> <li>Gamification increases engagement, motivation, and adherence in rehabilitation by giving clear goals, progress feedback, and rewards.</li> </ul>	<ul style="list-style-type: none"> <li>Data presentation should focus on trends and patterns, not raw values. Visual hierarchy, color coding, and dashboards should be used to reduce cognitive load.</li> <li>Interfaces should be intuitive, stepwise, and give meaningful insights for patients and therapists.</li> </ul> <p>→</p> <ul style="list-style-type: none"> <li>A mobile/desktop interface will be developed with dashboards showing progress, trends, and rewards; using color coding and simple graphs to make insights intuitive.</li> </ul>



Figure 71. A snapshot of the manufacturing process of the knee sensor sleeve, where the design part of the sleeve is being embroidered

## PHASE 4

# DELIVER

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This phase presents the final design, KinetiK. All components of the prototype are explained, the current data system is explained, and the interfaces are presented. In addition, the final concept is evaluated through validation testing and user testing.

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- 12. The final design: KinetiK
- 13. Validation evaluation
- 14. User test evaluation
- 15. Concept evaluation



Figure 72. The sleeve being positioned

## 12. The final design: KinetiK

This chapter explains all components of KinetiK, how data is collected and translated into insights, and presents the different user interfaces.

- 12.1 The concept
- 12.2 The sensor
- 1.3 The electronic components
- 12.4 The sleeve
- 12.5 Data collection and translation
- 12.6 The live graph
- 12.7 The interaction
- 12.8 User interfaces

### 12.1 The concept

KinetiK is a knee sensor sleeve designed for patients who are rehabilitating after knee surgery or injury. The name stands for kinematics and the idea of connection: connecting with your own movement. By giving insight into knee movements, KinetiK helps patients and healthcare providers better understand the progress of the recovery. Objective data on movement and development supports tailored rehabilitation and contributes to a more conscious and effective recovery process.



Figure 73. Both sides of the knee sleeve



Figure 74. Lunge exercise showing the front of the knee sleeve in bended position

## 12.2 The sensor

The knee sleeve is made of a black polyester-elastane fabric. The conductive yarn section consists of several parts.

1. The sensor works based on a change in contact points with stretch, which leads to a changing electrical resistance. This resistance can be measured and linked to knee angles. The sensor has a length of 14 cm, allowing it to cover the entire kneecap, even on larger knees. This ensures that knee stretch is used optimally without making the sensor unnecessarily long. Since little to no stretch occurs on the thigh and shin, no sensor is required in those areas. Furthermore, a shorter sensor results in a greater change in resistance. In a shorter sensor, the zigzag pattern is pulled further apart, leading to a larger change in contact points. The sensor was manufactured using a commercial sewing machine. During sewing, the fabric was pre-stretched by 25% using a frame in which the fabric can be clamped and stretched to various levels (Figure 76).
2. The connection section between the sensor and the electronic components is sewn directly onto the sensor at a lower stitch density. This section curves to the right, as it was previously determined that the electronic components would be positioned on the lateral side of the thigh. Since the conductive thread cannot be soldered, ShieldIt Super was used: a conductive fabric that is ironed onto the base fabric. In this area, the thread is sewn at a higher stitch density to increase contact with the conductive fabric.

**Non-stretch fabric**

**SHIELDIT SUPER**

Connection between  
yarn and wires  
Yarn width: 5mm  
Density: 1mm

**Connection part**  
between sensor and  
electronics  
Width: 5mm  
Density: 4mm

**Sensor**  
Width: 5mm  
Density: 0.5mm  
Pre stretch: 25%

**Fabric:** 78% polyester  
Black 22% elastane

Figure 75. The sensor section of the sleeve consisting of different parts



Figure 76. The sensor is stitched while being stretched using a stretch frame, which allows the fabric to be stretched to different extents.

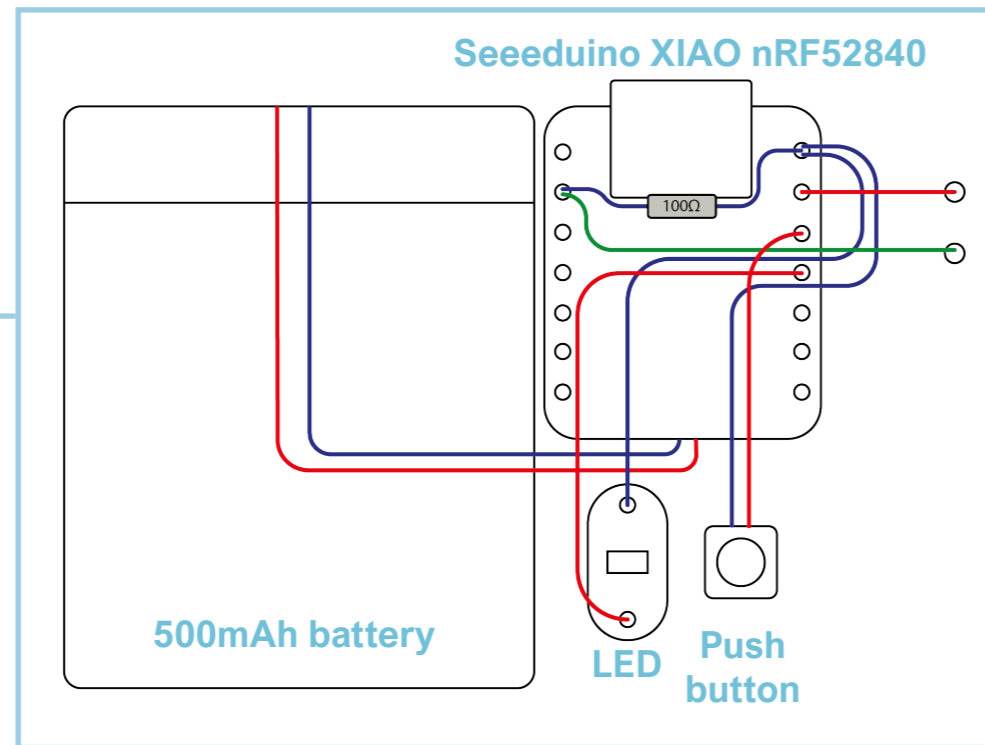
## 12.3 The electronic components

The electrical circuit of the prototype consists of (Figure 78):

1. A Seeeduino XIAO nRF52840. This is the microcontroller that reads the strain sensor values and sends them to a central device via Bluetooth Low Energy (BLE). The sensor circuit also includes a 100ohm resistor that the XIAO uses to compare the resistance of the strain sensor with. This very low resistance results in a fairly high power consumption. However, this is necessary to maximize the measured voltage difference and thus measure the changed resistance as precisely as possible.
2. A 500mAh Lipo battery. This battery can power the XIAO for 8 hours. As mentioned in the Scope chapter, energy consumption optimization was not considered. By optimizing battery consumption by putting the XIAO into low-energy mode when it is not measuring, the battery lasts longer and offers opportunities to reduce battery size.
3. A push button. The push button functions as an on/off switch; it is designed to turn the device on and off when it's in use or not. The push button

was chosen over alternatives like a toggle or slide switch because it is easy to operate and can be easily incorporated into the knee sleeve. In addition, the push button is a momentary button, meaning it doesn't have a true on/off position. When the button is pressed, the system switches between active use and a low-energy mode. In this mode, the electronics still consume energy, but very little, extending the battery life. True on/off buttons are less compact and therefore more difficult to integrate into the knee sleeve. For this reason, a compact momentary button was chosen, which is both user-friendly and easy to install. A LED. The LED lights up when the device is on, giving the user physical feedback about the device's activity.

The wires were soldered to the ShieldIt Super using low-temperature solder paste, as direct soldering melts the material through contact with the soldering iron. To add strength, these wires were sewn over.



Thin wires with a diameter were used within the circuit to keep the setup as compact as possible. Although the non-stretchable fabric relieves the strain, the bending of the knee sleeve must be taken into account when chosen the wiring length. If the wires are too short, the bending between the sensor and the electronic components can cause them to pull loose.

Figure 79 shows a schema of the circuit. The dark blue lines represent the GND/- wiring, while the red lines indicate the + wiring.

### Protection

To protect the components, they are housed in a leather pouch. This protects them from bumps and scratches, while being flexible and forming comfortably to the thigh. A square cutout has been made above the indicator light, ensuring the light is visible to the user (Figure 80).

### Maximalise stretch

To maximize the stretch that occurs during bending, an additional piece of anti-slip elastic has been placed at the top of the sensor. This ensures that the strain sensor can be stretched to its maximum capacity by preventing the fabric above the sensor from absorbing part of the stretch (Figure 80).



Figure 78. The composition of the electronics on the sleeve

Figure 79. The wiring of Kinetik

Figure 80. The leather protection pouch and extra antislip to increase stretch of the sensor

## 12.4 The sleeve

### The design

The outer layer of the knee sleeve has multiple functions; serving as protection, as positioning cue, and as a design element (Figure 81).

1. Protection  
The outer layer covers the entire sensor to protect it from external forces that could lead to wear or tear.
2. Positioning cues  
Double lines with a circle were used for positioning, as these provided the best results during testing.
3. Design  
The design is inspired by the flow of current through the knee sleeve. Although the sensor itself is not visible, the design gives insight into the knee sleeve's operation and emphasizes its unique functionality as a special product.

To prevent friction between the wires in the outer layer and the sensor, an additional piece of fabric was added on the inside of the outer layer where it touches the sensor (Figure 82).

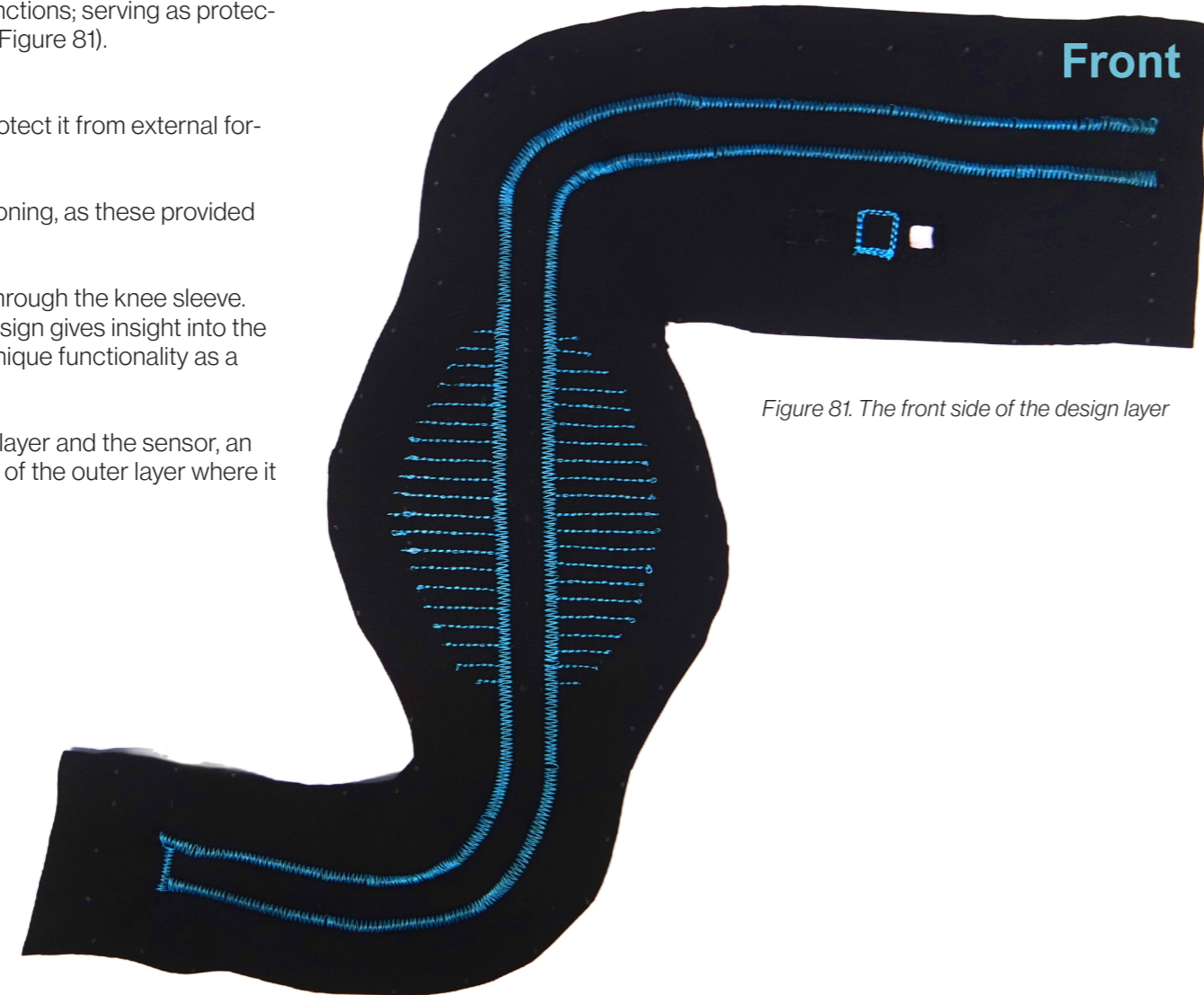


Figure 81. The front side of the design layer

### Comfort

The knee sleeve is made of a polyester-elastane composition. This smooth, stretchy sports fabric increases comfort during exercises. The knee sleeve is held in place by anti-slip elastic bands at both the top and bottom. The rigid electronics are positioned on the side of the leg, as this was considered the most comfortable and unobtrusive area.

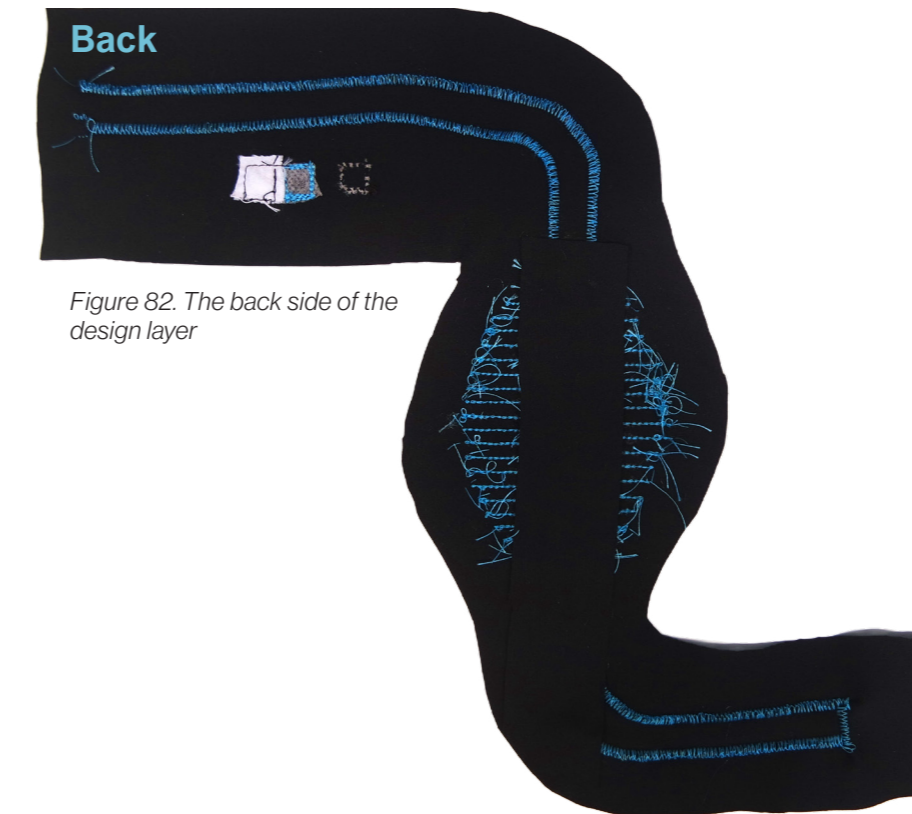


Figure 82. The back side of the design layer

Figure 83. The design added onto the knee sleeve



## 12.5 Data collection and translation

### Data collection system

Each knee sleeve contains a Seeeduno XIAO microcontroller, which reads the data from the strain sensor via an Arduino script and transmits it wirelessly via Bluetooth Low Energy (BLE).

The measurement procedure (figure 84):

#### 1. Analog sensor measurement

The strain sensor is connected to an analog input on the Seeeduno XIAO. The sensor gives varying resistance values depending on the degree of strain during knee flexion. A voltage divider converts this resistance into a voltage, which the microcontroller can read and convert into a resistance value.

#### 2. Conversion to knee angle

The measured strain is converted into a knee angle in degrees via a calibration table. This creates a continuous time series of knee angles.

#### 3. Noise reduction

To reduce measurement noise, the measured angle is filtered with a simple low-pass filter. This cancels sudden measurement peaks resulting in a more stable signal.

#### 4. Data transfer

The filtered angle values are transmitted in real time via BLE and can be received by the Python software. The Python code monitors the left and right sensors and visualizes the data in a live graph with corresponding timestamps.

Appendix D and E contains the Arduino and Python code, along with further explanations of their functions.

### Raw data to insights

The collected knee angles can be analyzed to monitor the rehabilitation progress. The timestamps and the measured resistance/angle can be used to calculate various insights (figure 84).

#### Exercise Time

Exercise time is the duration a user actively performs an exercise. The exercise starts and stops when the user clicks “Let’s Start” or “Next Exercise.” The time is calculated by the difference between the first and last measured timestamps.

#### Flexions

The number of flexions a user performs during an exercise. A flexion is detected as a wave in the angle data, from fully extended (minimum measured angle) to flexed (maximum measured angle) and back again. Two consecutive peaks and troughs are recorded as one flexion.

#### Intensity

Intensity indicates how vigorously an exercise is performed. Intensity combines the speed of the flexions with the height of the flexion angle. High peak values in the angle graph combined with a high velocity indicate high intensity.

#### Asymmetry

Asymmetry indicates the difference between the left and right knee during exercises. The peak values of the left and right sensors for the same flexion are compared: a large difference indicates high asymmetry. Comparing the time between peaks and the overall waveforms of the left and right knees can indicate delayed movement of the injured knee.

#### Consistency

Consistency measures how evenly the user performs the exercises. Consistency can be measured by comparing the height of peaks (flexion angle) and the width of the waveforms (flexion velocity) in the angle data. Large variations indicate inconsistent performance.

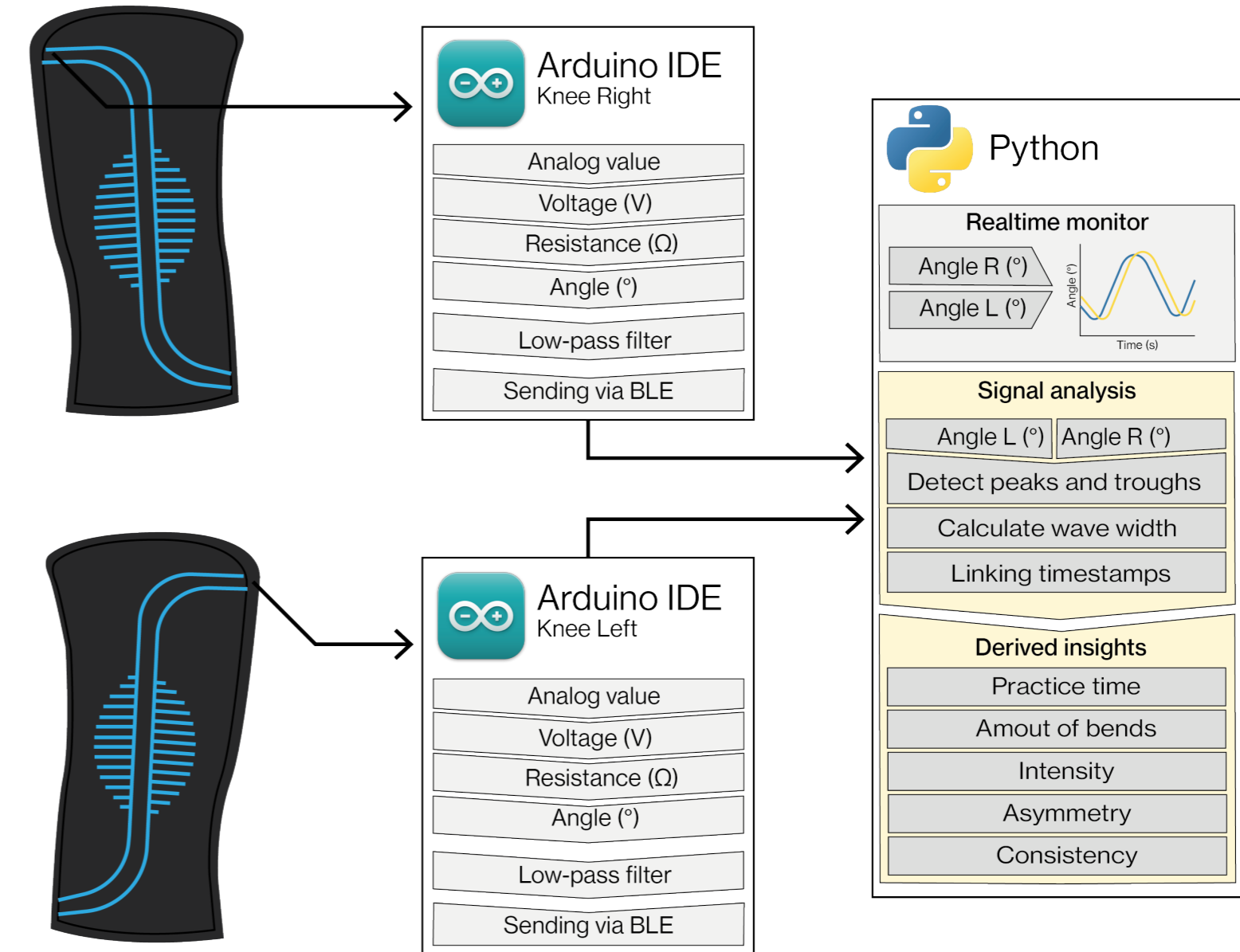


Figure 84. Analog values are collected by the microcontroller, processed, and sent to Python, which generates a graph of bending angle versus time

## 12.6 The live graph

### The graph line

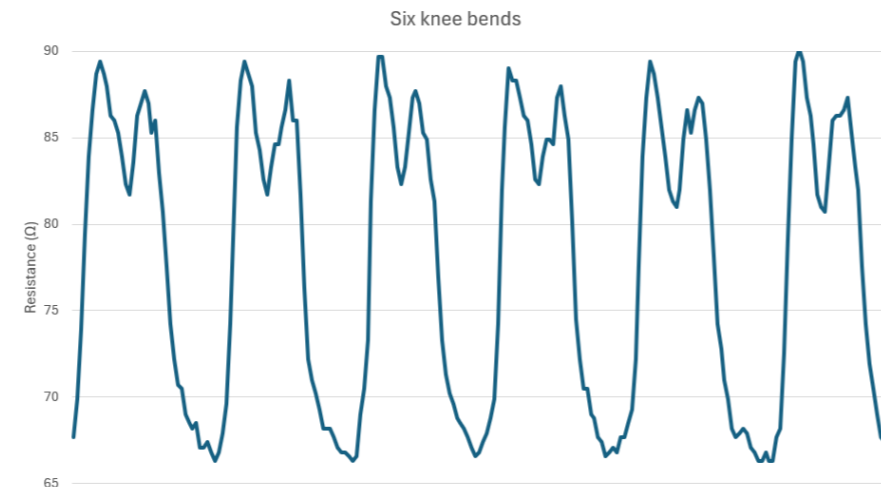
Figure 85 shows the graph of the resistance change during six consecutive knee bends. When zooming in on a single bend, it can be seen that the electrical resistance of the strain sensor increases when the knee flexes (Figure 86). This increase corresponds to the strain in the fabric by the increasing knee angle.

Just before the resistance line returns to its initial value, a small local dip is visible. This dip represents the short moment when the knee is held in the maximum flexion position. During this static moment as mentioned earlier, a relaxation effect occurs: because the knee and thus the textile remain temporarily in a fixed position, the conductive fibers in the sensor are able to restructure themselves, resulting in a slight decrease in the measured resistance.

When the knee starts moving again and the extension phase begins, a small peak in resistance is observed. This peak can be explained by the viscoelastic properties of the textile and the internal friction between fibers and yarns. When the material is reloaded, a short increase in internal tension happens, which translates into an increase in resistance (Panahi et al., 2023; Luo & Stylios, 2024). This peak thus marks the transition from a static to a dynamic phase in the movement of the knee.

During the user test, which will be discussed later in the User test evaluation section (Chapter 14), the patient indicated that this second peak coincided with the moment he began to feel his knee. This observation suggests that the second peak is not just a characteristic of the sensor signal, but coincides with a transition in movement perceived by the user.

Figure 85. sensor performance on the knee over six bending cycles



Stop flexion    Start extension

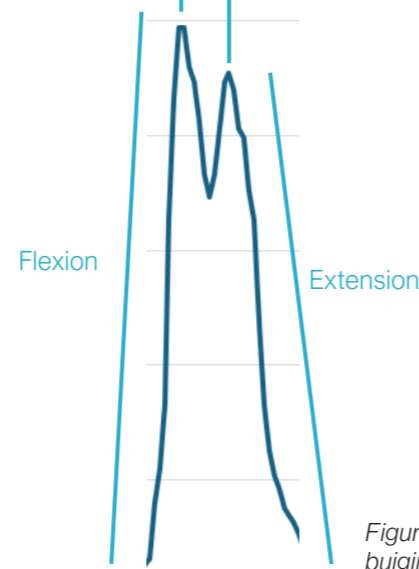


Figure 86. Explanation of one buiging; flexion and extension

### Low-pass filter

To reduce noise and small fluctuations in the sensor signal, a simple low-pass filter is added in the Arduino code. A low-pass filter allows slow changes in the signal to pass through, while rapid variations, often caused by measurement noise or micro-movements in the fabric, are toned down. This results in a smoother resistance line in the graph.

The filter combines new measurements with earlier ones, which reduces sudden changes while keeping the overall knee movement. The strength of the filter determines the extent to which the signal is smoothed: a stronger filter gives a smoother line, but can make characteristic details, like the small dip when holding the maximum flexion, less visible, as shown in the figure 88. In addition, a filter that is too strong leads to a reduction in the measured resistance peak.

A balance is therefore needed between suppressing noise and between filtering out noise and retaining meaningful signal information. In this application, a filter setting has been chosen that smooths the line without changing the underlying signal shape (Figure 87).

Figure 87. The graph of six knee bends using a medium filter

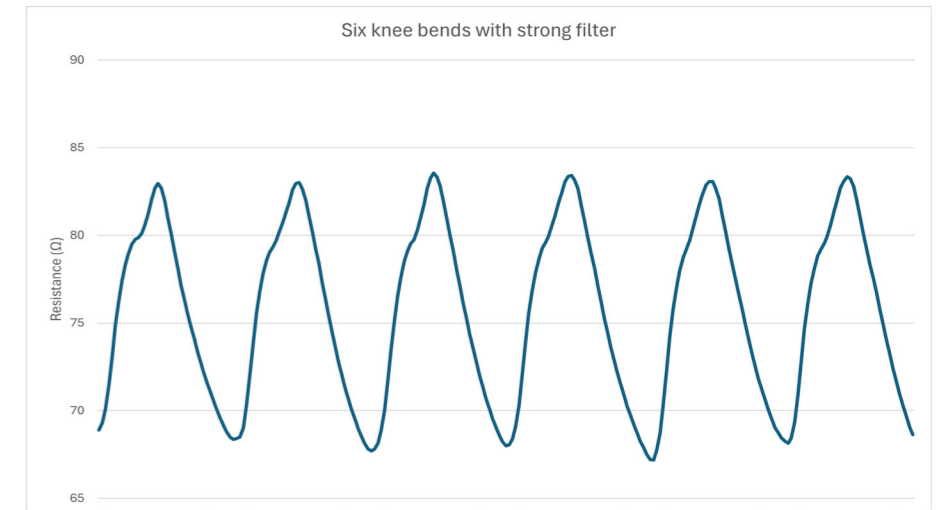
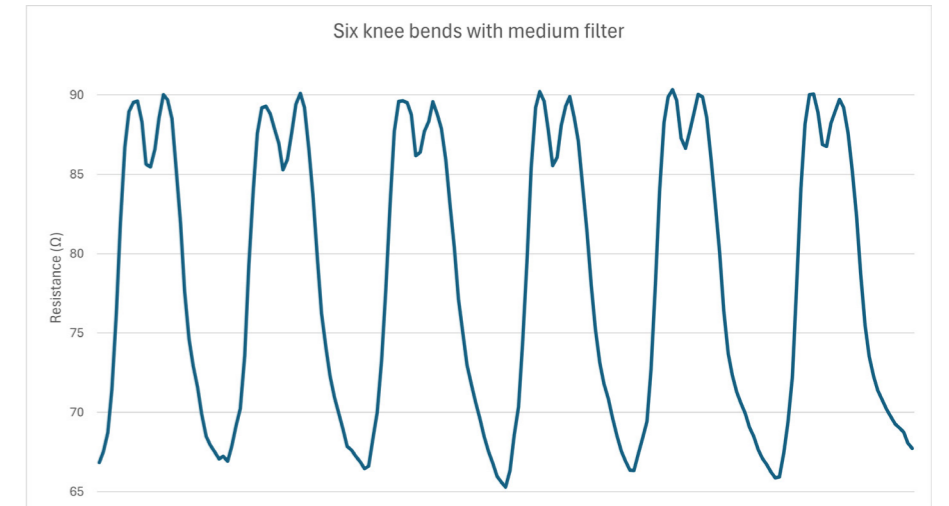


Figure 88. The graph of six knee bends using a strong filter

## Measurement using two knee sleeves

The interview with the physical therapist showed that symmetry between an injured and a healthy knee is an important indicator in the rehabilitation process. In particular, the difference in movement pattern and load capacity between both knees gives healthcare providers insight into the progress of recovery and the moment when a patient learns to move symmetrically again. Continuous, objective measurement of this asymmetry during exercises is therefore considered very valuable, especially in a home situation where direct observation by the physical therapist is not possible. Based on this need, this project decided to develop two knee sensor sleeves so that the movement of the injured knee can be directly compared to that of the healthy knee.

Figure 89 shows a squat movement in which the movements of both knees were measured and plotted in a graph. In order to measure the same movement as closely as possible, the left knee sleeve was calibrated using the right knee sleeve as a reference. During squat movements, the resistance values of both knee sleeves were measured and compared. Using conversion factors, the measurements from the sensor in the right sleeve were adjusted during new squat movements so that they corresponded as closely as possible to the sensor in the left sleeve.

Nevertheless, small deviations remain between the left and right knee sleeve. The sensors in the knee sleeves were produced using a sewing machine with limited adjustment accuracy, resulting in variations in the sensors. This causes differences in the sensors' responses to knee bends. The sensor in the left sleeve responds slightly differently to knee movements, which is visible in the peak heights and moments and a slightly bigger hysteresis, which is visible in the difference in the decreasing extension lines.

Figure 90 shows a walking pattern of two knees. It shows an alternation between flexion of the right and left knee.

## Asymmetry measurements

Symmetry can be expressed in two ways: ROM symmetry and movement symmetry. ROM symmetry refers to the difference in range of motion between the knees, or how far each knee can bend. Movement symmetry describes the symmetry of the knees during an exercise such as squats, where the injured knee may lag behind in movement. ROM differences are

Figure 89. Eight bending cycles measured by two knee sleeves during a squat exercise

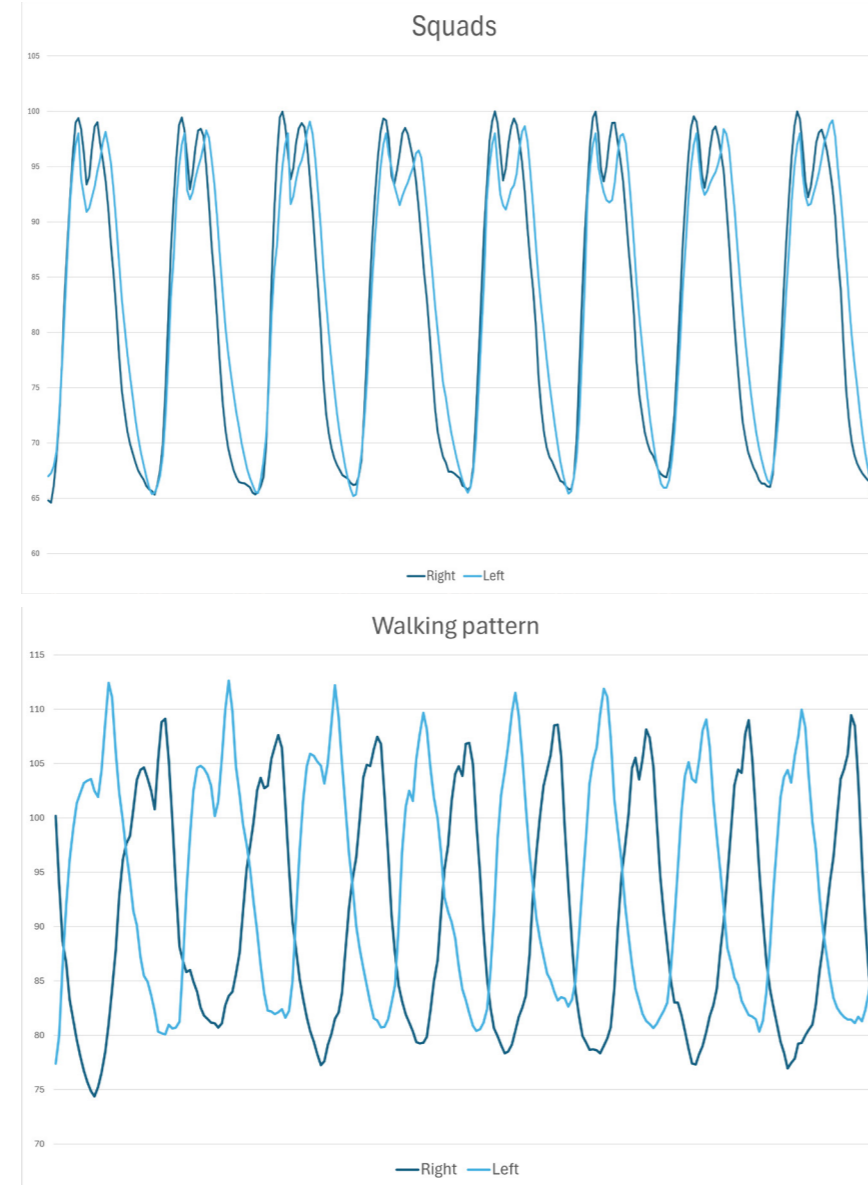


Figure 90. Eight bending cycles measured by two knee sleeves during gait

often large, 40–50% in the early stages of rehabilitation, while movement asymmetry is usually only a few degrees and therefore needs to be measured more accurately.

Movement symmetry can be further subdivided into flexion symmetry, which examines whether the injured knee flexes less, and speed symmetry, which assesses whether the injured knee lags behind in movement (Figure 91). Absolute measurement accuracy is less critical for measuring ROM symmetry, whereas for movement symmetry it is important that both sensors provide comparable values under the same conditions.

As mentioned, the sensors in current knee sleeves respond slightly differently to the same knee flexion, which means that precision in movement symmetry is still too limited. In a large-scale production environment, with more accurately adjustable machines, it would in principle be possible to produce sensors that respond almost identically. This could be an important

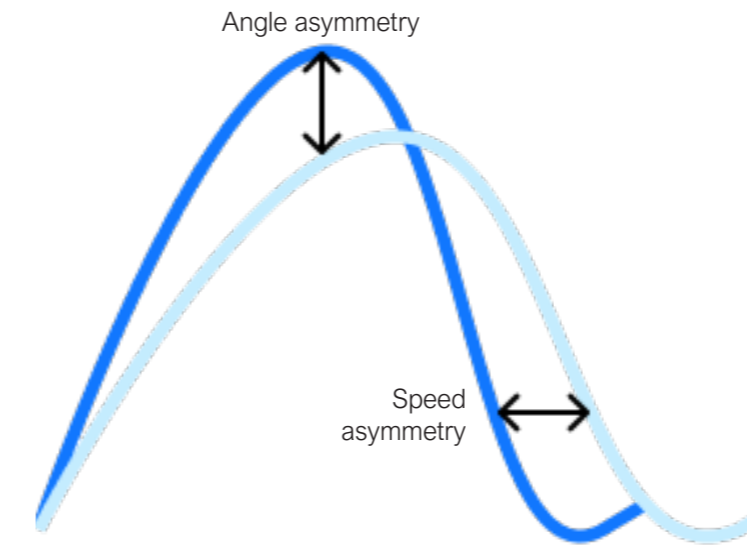


Figure 91. Explanation of types of symmetry

step in reducing the current variations and improving reliability in measuring movement symmetry.

## Calibration method

Various tests conducted during this project showed that the shape of the knee and the exact positioning of the knee sleeve have a significant impact on the measured data. Despite correct placement using visual cues, small differences in positioning can lead to a different distribution of stretch in the fabric during flexion. This means that sensors, although identical in construction, can still give slightly different measurements for the same movement because of a slightly different placement.

In order to link the correct flexion angle to the measured resistance values and to measure symmetry between both knees, some form of calibration is necessary. To keep the concept user-friendly for patients, this calibration should not be too complex and should not take much time and effort. Calibration based on a zero measurement with a stretched knee is not sufficient, since positioning variations affect both the offset and the sensitivity of the measurement. At the same time, in the early stages of rehabilitation, the injured knee cannot fully bend, which limits calibration methods that assume a full range of motion.

A possible approach is to first calibrate the knee sleeve on the healthy knee. This can be done by fully bending and stretching the knee (0-130°) several times, so that a calibration table can be created that links the measured resistance values to the actual knee flexion angle. The knee sleeve for the injured knee can then be calibrated by matching it to the already calibrated healthy knee sleeve, which allows relative comparisons between the knees. One possible approach to this is to let the patient perform a few controlled squat movements to the maximum angle that is still comfortable, moving both knees as symmetrically as possible.

However, this calibration method has not yet been tested or validated, and further possibilities have not been explored in depth. The method relies on assumptions like a fixed maximum knee flexion of 130° of the healthy knee and symmetrical execution of movements, which could be challenging for patients during rehabilitation. Therefore, further research is needed to investigate calibration methods that are both reliable and user-friendly. These methods should be validated under practical use conditions.

## 12.7 The interaction

The knee sensor sleeve is purchased by the patient themselves on the advice of the physical therapist. Because of the relatively low production costs (Appendix G), the sleeve remains financially accessible. Personal ownership offers advantages in terms of hygiene, as the textile sleeve is worn directly on the skin and is used intensively. In addition, use by a single person allows calibration to be maintained, meaning no limited recalibration is needed before each session. Furthermore, ownership increases patient involvement, which contributes to consistent use and better data quality during rehabilitation in and outside the practice. Finally, this choice avoids additional tasks for the physical therapist, like inventory management and maintenance.

The knee sleeve can be turned on by pressing the blue square (1). The led to the left of the button lights up to indicate it is on and active. To ensure accurate measurements, the user is asked to stretch the knee sleeve a few times before each use to stabilize the fibers and contact points (2). The blue lines on the knee sleeve help the user positioning it correctly around the knee (3).

The user opens the KinetiK app, connects to both knee sleeves, fills in the exercises to be performed, and starts their exercises with a graph shown in the app that guides his throughout the exercises (4,5). After completing all exercises, the patient can analyze his results. The concept is designed to allow the patient to analyze the results both independently and together with his physical therapist (6).

After exercises, or at any time, progress over the month or multiple months can be viewed, and exercise sessions can be scheduled in the calendar (7). Afterward, the user simply places the knees sleeves on the charger, by connecting a USB-C cable to the USB-C port above the power button, so they are fully charged and ready for use the next session (8).

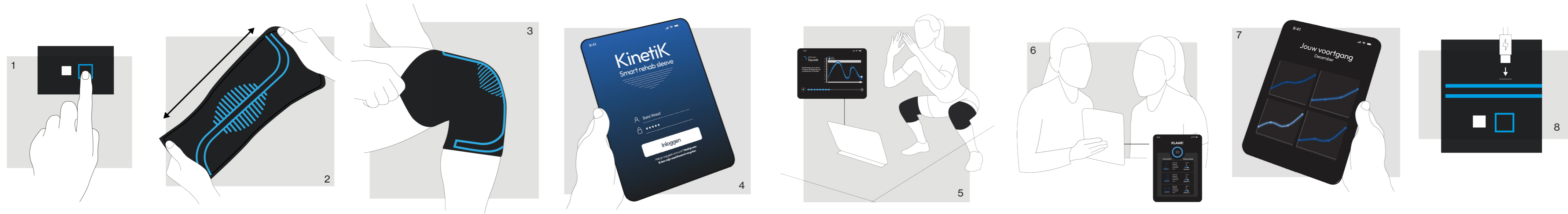


Figure 92. The envisioned user interaction

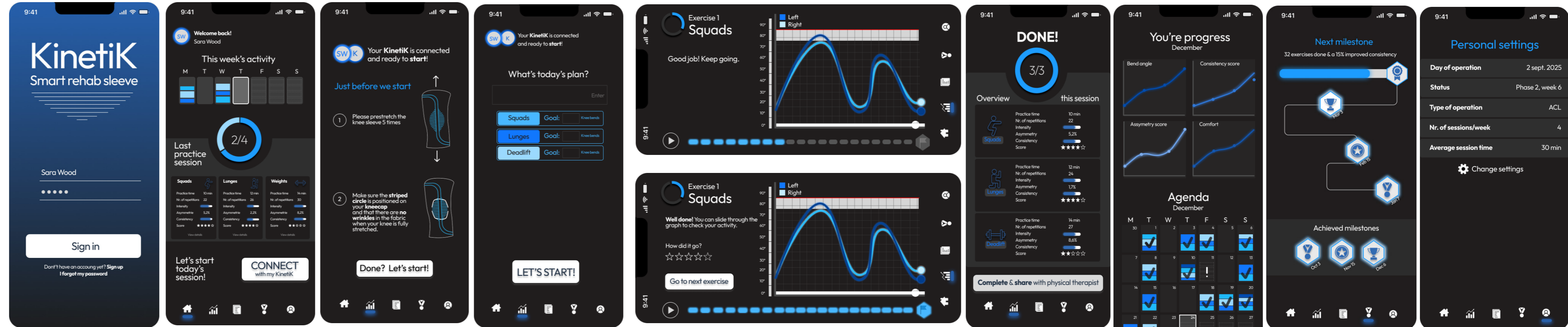
## 12.8 User Interfaces

### Patient

The user interface of the patient is based on insights gained from the user interface research earlier in this report (11. User Interfaces). The interface consists of six pages:

- The login page
- The dashboard/home page
- The real-time page
- The overview page
- The batch page
- The settings

An explanation of what can be seen is provided below the visualizations (Figure 93).



Each patient has a personal account displaying only their own measurements. By logging in with a personal login, the user gets secure access to this individual data.

After logging in or opening the app, the page shows an overview of the current week's activities. The various blocks represent the performed exercises. Information about the most recent exercise session is also displayed, and there's a button to connect to the knee sensor sleeve to directly start the practice session of the day.

Before starting the exercises, the user is asked to pre-stretch the knee sleeves a few times and then position it correctly.

In consultation with the physical therapist, the user can fill in the exercises included in the session and how many bends should be performed per exercise. This schedule forms the basis for guidance during the session. Including this step enables the possibility to receive exercise specific insights.

During the exercise, the user is guided in real time by a line graph that displays the flexion of both knees. The target flexion for that day is automatically calculated based on previous performance and displayed as a white reference plane in the graph. A red maximum line is also shown to prevent overload.

Each time a bend is performed above the target angle, a box in the progress bar at the bottom of the screen turns blue. This bar provides insight into the exercise's progress. After completing the exercise, the user can scroll through the graph to compare individual bends.

The user can then rate the exercise on a scale of 1 to 5. With a low score, potential causes, such as overload due to excessively large bend angles or high movement speed, can be identified from the derived insights.

After completing all exercises, the user receives an overview of the exercises performed and the retrieved insights. This information can be viewed independently or discussed with the physical therapist. By clicking the Complete & Share button, the user confirms that the session data will be made available to the physical therapist.

The progress screen displays graphs with insights over a month and the full rehabilitation period. It also includes a calendar showing completed and skipped sessions, and allows exercises to be scheduled.

After completing a rehabilitation phase, achieving a specific bending angle, or completing a certain number of exercises for example, badges can be earned. The badge screen shows which badges have already been earned and the progress toward the next badge.

Because every rehabilitation process is unique, various parameters can be adjusted in the settings screen, like the current rehabilitation phase, the number of exercise sessions per week and the average exercise duration per session.

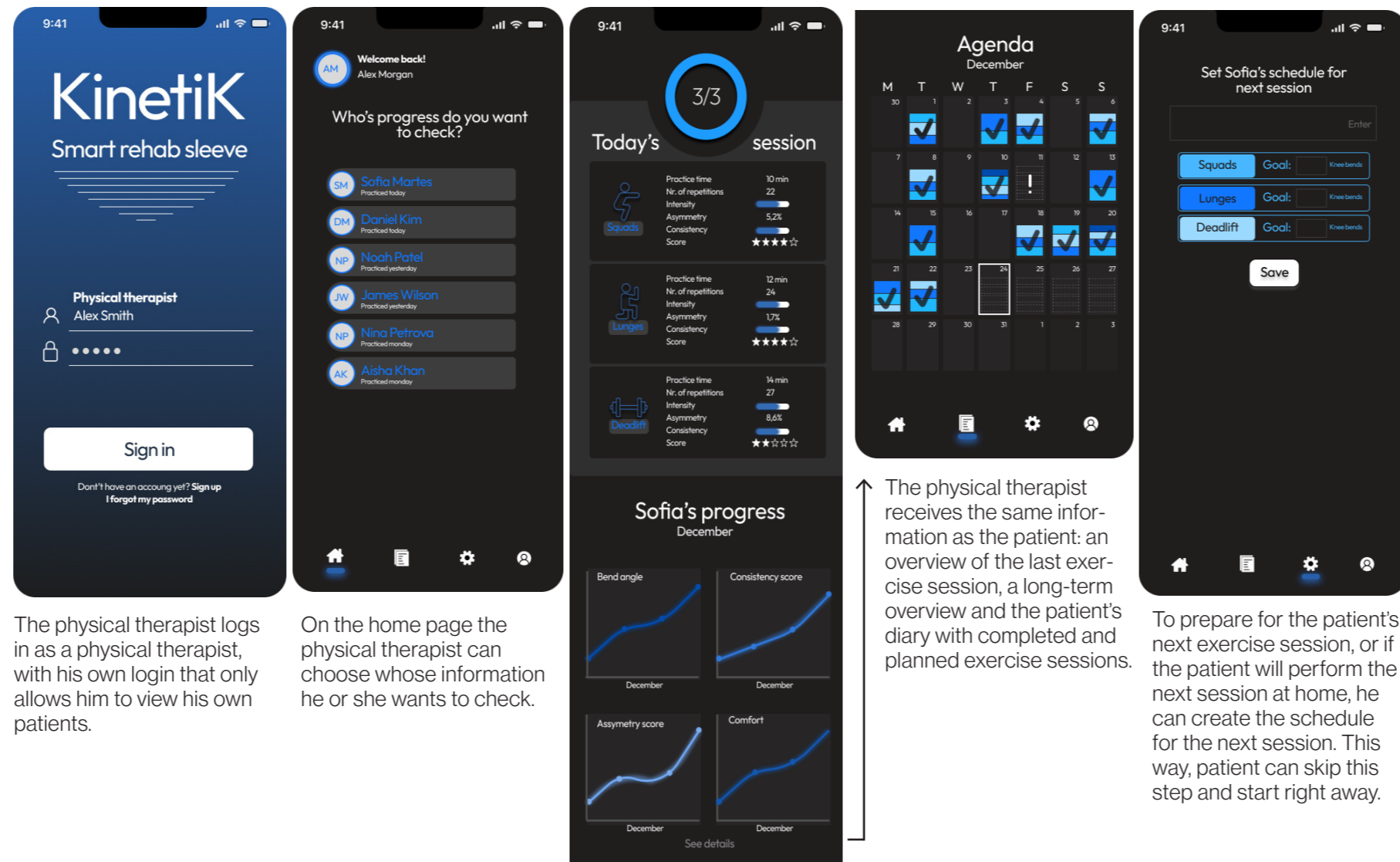
Figure 93. The pages of the user interface for the patient with explanation

## Physical therapist

The physical therapist's interface is kept as simple as possible to allow for quick access and assessment of the information. The physical therapist sees the same information as the patient, but within a single page.

The physical therapist's interface consists of the following pages (Figure 94):

- The login page
- The dashboard/home page
- The overview page
- The planning page



The physical therapist logs in as a physical therapist, with his own login that only allows him to view his own patients.

On the home page the physical therapist can choose whose information he or she wants to check.

The physical therapist receives the same information as the patient: an overview of the last exercise session, a long-term overview and the patient's diary with completed and planned exercise sessions.

To prepare for the patient's next exercise session, or if the patient will perform the next session at home, he can create the schedule for the next session. This way, patient can skip this step and start right away.

Figure 94. The pages of the user interface for the physical therapist with explanation

## Orthopedist

Because of the limited involvement of the orthopedist and the focus solely on long-term overviews, it was decided not to develop a separate interface for them. The number of shared overviews they would like to receive is too small to justify a separate app.

The physical therapist interviewed previously therefore recommended adding an export function within the physical therapist interface. This allows progress graphs to be exported, for example, to a PDF, and then sent to the orthopedist. This way, the orthopedist can still gain insight into the patient's progress without the need for a separate app that is only used to a limited extent.



Figure 95. A snapshot of the manufacturing process of the test setup

## 13. Validation evaluation

This chapter describes how the validation test was conducted, the insights obtained from these tests, and the conclusions that can be drawn from the results.

- 13.1 Test focus and setup
- 13.2 Results
- 13.3 Evaluation
- 13.4 Work range check
- 13.5 Discussion and conclusion

### 13.1 Test focus and setup

To assess the reliability and applicability of a textile knee sensor sleeve with an integrated strain sensor, it is important to test it not only under ideal laboratory conditions but also in a setting that approximates real-world conditions as closely as possible. Previous measurements on textile samples gave valuable basic information about the sensor's electrical behavior, but did not give insight into its performance when exposed to complex, dynamic, and anatomical conditions around the knee.

The knee is a challenging measurement environment because of the combination of flexion, stretch, compression, and the movement of textiles over the skin during movement. These factors can influence the measured resistance. Therefore, it is important to investigate how the sensor behaves when worn around the knee and when the knee flexes to various angles, both in static positions and during movement. This way it can be determined whether the sensor produces consistent and reproducible measurements.

The tests performed using a setup in which the knee is positioned at various angles in a controlled manner allow for analysis of the sensor's response behavior around the knee. By performing measurements both at rest and during movement, it is possible to assess how static and dynamic loads affect the resistance values. This test phase is therefore an important step in validating the sensor.

#### Goal of the test

The goal of this test is to evaluate the behavior, reproducibility, and practical applicability of the knee sensor sleeve when worn around the knee. It investigates how the integrated strain sensor responds to different static knee angles, dynamic movements, and variations in movement conditions. These tests should show the extent to which the sensor can give useful and reliable information for rehabilitation monitoring.

#### Research questions (RQ)

This test was conducted to answer the following research questions:

- What is the response behavior and sensitivity of the integrated textile strain sensor at different knee flexion angles in a static position?
- How does the sensor output vary during dynamic knee flexions compared to static positions, and what influence do movement speed and starting position have?
- What is the reproducibility of the sensor measurements during repeated movements, within a single session, after multiple flexions and after repositioning of the sleeve?
- What is the effective work range of the sensor in the integrated knee sleeve, and is this sufficient for the full range of knee flexions during rehabilitation exercises?

#### Test focus/measurements

During the test phase, the sensor response was measured not only at fixed knee angles at rest, but also during active knee movement from a fully extended position ( $0^\circ$ ) to various flexion angles. This approach was chosen because previous measurements showed that the measured resistance during movement differs from the resistance measured when the same angle is maintained at rest.

During dynamic knee bending, the textile sensor is quickly stretched. As discussed before, due to the viscoelasticity of textiles and the internal friction between fibers and yarns, a temporarily higher internal tension arises than when the same knee angle is maintained at rest. This increased tension results in a peak in the measured resistance. When movement stops and the knee remains in a stable position, sensor fibers gradually rearrange and settle, resulting in the resistance stabilizing to a lower, static value (Panahi et al., 2023)(Luo & Stylios, 2024).

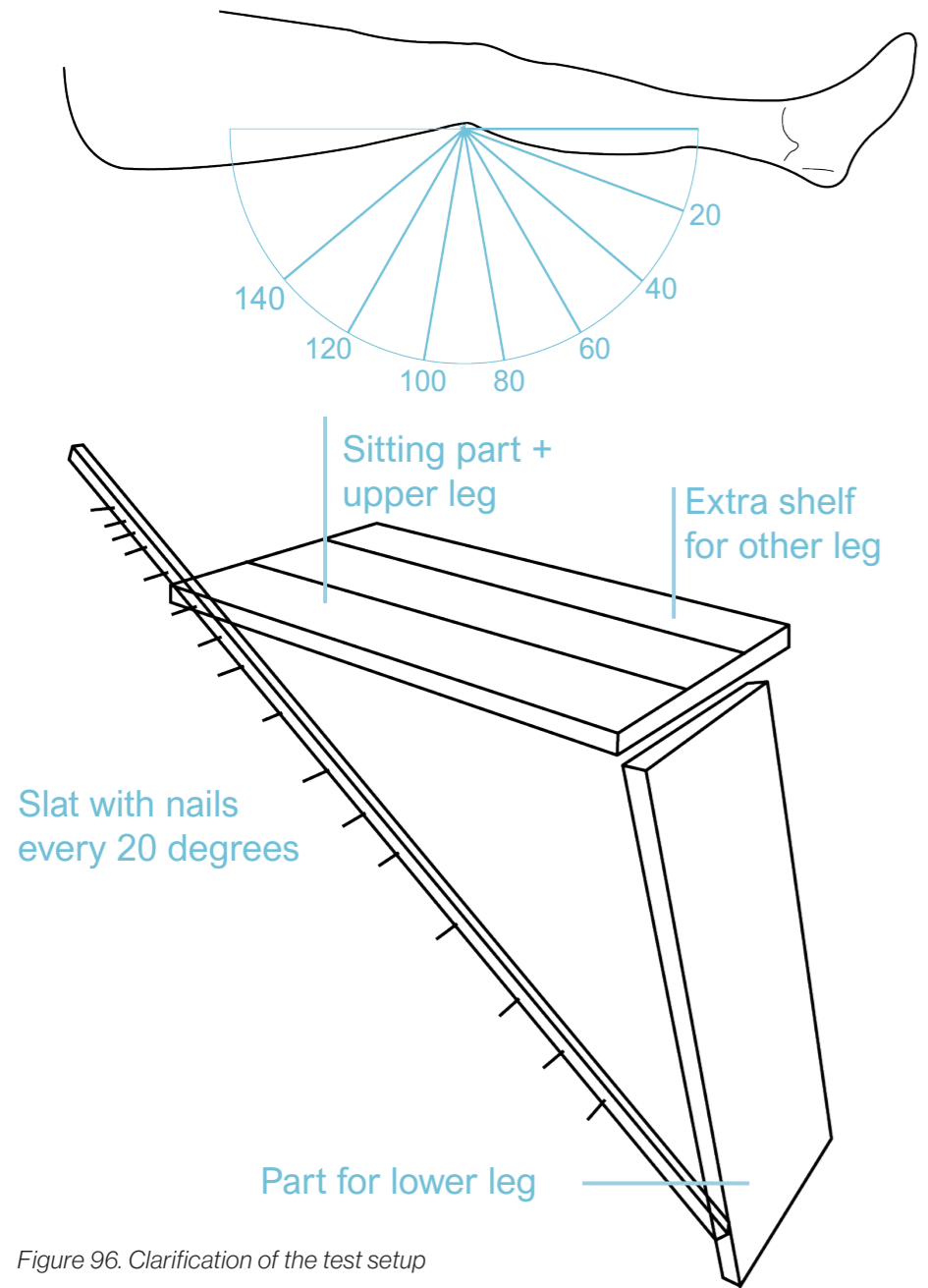


Figure 96. Clarification of the test setup

The distinction between measurements during movement and measurements at rest is therefore important for interpreting the sensor output. In a realistic rehabilitation situation, the sensor will be continuously exposed to dynamic knee movements. By testing both measurement conditions, it can be better determined how the sensor responds to movement, the difference between dynamic peak values and static measurements, and which measurements are most suitable for determining knee flexion in this case.

### Test setup and plan

To perform these tests, a test setup was created that allows the knee to be held at a specific angle (Figure 96). The setup consists of a seat section on which the thigh rests and a lower leg section. A hinge is placed between these two sections, where the back of the knee will be located. This allows the knee to be placed on the setup and brought into a determined position, or knee angle.

A slat is placed on the side of the setup, attached to both planks with screws. This slat is used to fix the angle between the planks. During the setup, the angles were measured using a digital goniometer (Figure 97, 98). The screws in the slat are positioned so that the planks are held at fixed angle increments of 10 degrees (10°, 20°, 30°, 40°, and so on)(Figure 100). Because the setup is handmade, the set angles have a deviation of up to a maximum of 2 degrees.

To ensure the test person sits upright to perform the measurements correctly, an additional plank was placed on the side of the untested leg. The setup shown in the illustration and photos is intended for measurements on the right leg. For measurements on the left leg, both the additional plank and the positioning slat were placed on the opposite side.

For angles smaller than 80 degrees, support was added (Figure 99). Without this support, the weight of the leg would cause the plank to sag slightly, which would cause a deviation in the set angle.

Figure 97. The desired angles were measured with a goniometer



Figure 98. Holes have been drilled in the slat at the desired angles to fix it in the desired position with a screw



Figure 99. Support is used for small angles up to 80°



Figure 100. the lower leg plank is positioned using preset screws



Figure 101. In this image, measurements are being taken on the right leg. The leg is positioned at a 100-degree angle using the measurement setup.

The image on the left shows the test setup. The test person is positioned on the setup with the leg to be tested on the hinged side of the board. The test person remained seated on the setup throughout the test cycle, while the setup, and therefore the knee, was adjusted to a different fixed angle each time. The resistance values were read out as numbers and via the generated graph in Arduino.

# 13.2 Results

## Results static measurements

### Statistical measurements at various knee angles

The first set of measurements consisted of determining the stable resistance value for each knee angle. The knee was positioned at a specific angle using the test setup and then waited until the sensor resistance had stabilized. This value was recorded. Each angle was measured three times in three different cycles:

1. The first measurement round, the knee was placed at the various angles.
2. The second measurement round, the first measurement round was repeated after 15 full knee flexion and extension cycles, to determine the influence of movements performed on the sensor output.
3. The third measurement round, the first measurement round was repeated after removing and repositioning the knee sensor sleeve, to determine the influence of repositioning of the sensor.

The three measurements generally followed the same pattern, but there was a maximum deviation of approximately 1Ω between the repeated measurements (Figure 102). At the lowest (0–20°) and highest (80–140°) angles, the resistance change was minimal, while the largest changes were recorded between 20° and 80°. This indicates higher sensor sensitivity in the mid-range of the knee flexion, while the angles close to full extension and maximal flexion show lower sensitivity.

### Stretch distance test

To investigate whether the low change in resistance between the first and last angles could be explained by possibly reduced stretching of the sensor over the knee at these angle differences, an additional measurement was performed. For this, two lines were drawn on the knee at a distance of 15 when fully extended. The distance between these lines was measured with a measuring tape for the various knee angles. This distance represents the relative stretch of the material for the various knee angles. The change in distance across the angles was found to be fairly linear, meaning that the measured changes in resistance could not be explained by varying stretching of the sensor over the knee (figure 104).

## Results dynamic measurements

### Dynamic measurements during movement

A second set of measurements was performed while flexing the knee from 0° (full extension) to various angles. These measurements focused on the peak resistance values that occur during movement, as discussed previously. The knee was moved at an average speed of approximately 140°/s. As with the static measurements, three cycles were performed. For each specific angle, the measured resistance was determined by comparing the peak values of six consecutive bends and calculating their average.

The six consecutive peak values within one cycle were very close to each other, indicating good repeatability. However, the measurements of the 3 different cycles showed a similar pattern to the static measurements, but slightly more linear, with maximum deviations of up to 2Ω (Figure 103). Because these are peak values recorded during movement, the resistance at 0° itself was not included. However, upon returning from the specific angle to 0°, the measured value was systematically slightly higher at a higher starting angle (Figure 105). This indicates that the sensor does not have a single fixed zero value at full extension, but depends on the preceding angle and dynamic load.

### Influence of movement speed

To investigate the effect of speed on the sensor response, measurements were performed at two speeds: 140°/s and 70°/s (approximately twice as slow) at moving from 0° to 140°. At 140°/s, the measured values ranged from 72 to 97 Ω, while at 70°/s, the values ranged from 65 to 93 Ω. This shows a speed-dependent effect: higher speeds lead to higher measured resistances, which can be explained again with the previously discussed dynamic tension buildup in the textile and viscoelastic effects.

### Effect of starting position

Finally, the influence of the starting angle on the measured resistance was investigated. Measurements from 0° to 120° yielded a range of 104–133Ω, while from 100° to 120°, a range of 110–122Ω was measured. This indicates a slight influence of the starting angle or previous movements on the sensor value, which may be due to hysteresis and again the internal tension buildup in the textile structure.

Figure 102. Three cycles of static measurements

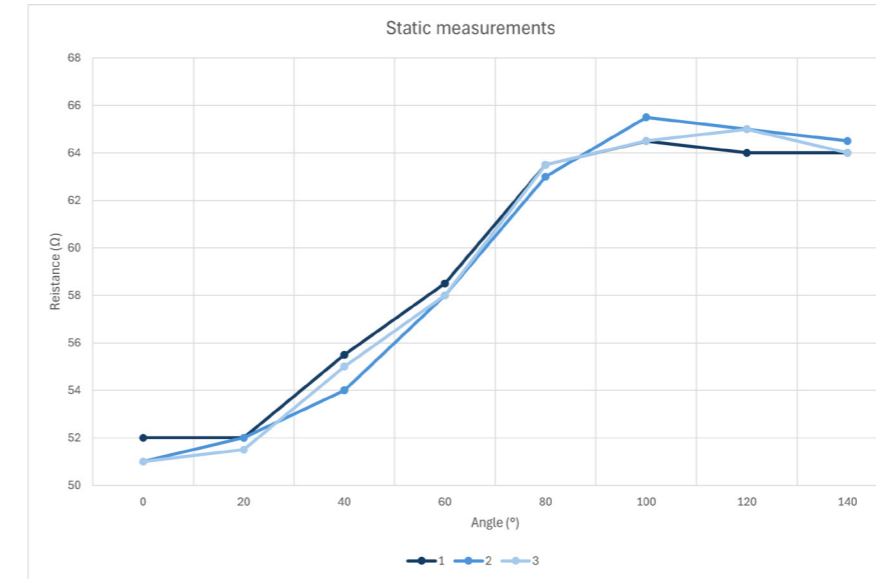


Figure 104. Measured stretch distances

Figure 103. Three cycles of dynamic measurements

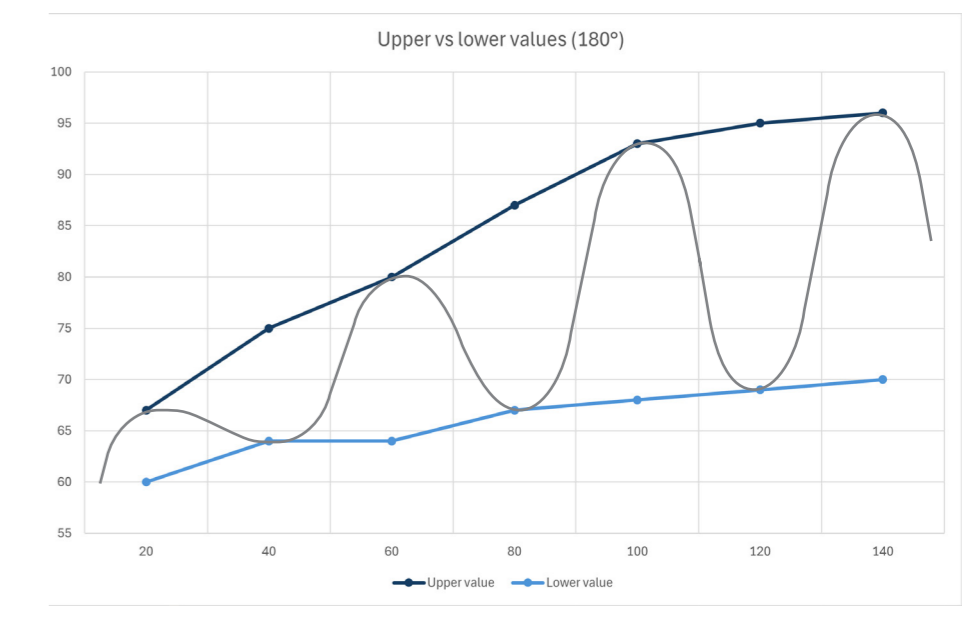
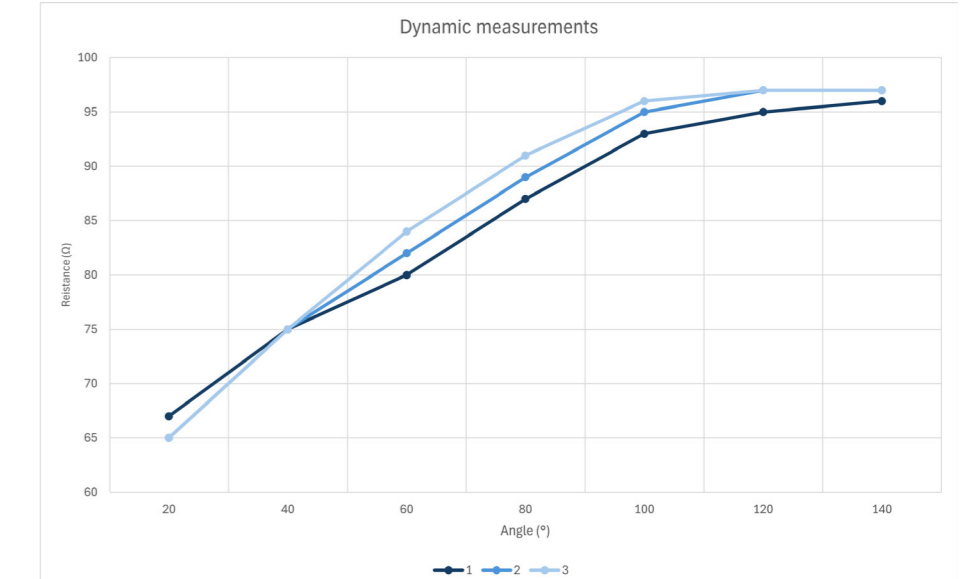


Figure 105. Measured upper and lower values. The gray waves are added to clarify what is meant with upper and lower values

## 13.3 Evaluation

### Evaluation

The results show that the sensor:

- Is sensitive in the mid-range of 20°–100° of knee flexion.
- Is less sensitive and thus reliable at extreme angles, possibly due to the mechanical properties of the textile and small strain changes that barely affect the resistance.
- Exhibits dynamic behavior: peak values during movement are higher than static values, and the sensor value during return movement depends on the preceding angle.
- Is speed-dependent: Higher bending speeds lead to higher measured resistances, which seems consistent with viscoelastic stress buildup in textiles.
- Is starting angle-dependent: The starting angle influences the measured resistance values, which seems consistent with mechanical hysteresis in textiles.

The measurements show that repeated cycles and repositioning of the sensor have a little effect, which shows sufficient reproducibility for the mid-angles. However, the maximum deviation of 1–2Ω is too much for accurate angle measurements.

### Conclusion and continue

#### Statistical vs. dynamic measurements

Static measurements provide stable values (range 51–65Ω) at a fixed knee angle at rest. The values between the angles of 20° and 100° are reproducible and well-suited for sensor calibration.

Dynamic measurements (range 65–96Ω) are recorded during active movement and show larger resistance changes between different angles.

Because a rehabilitating knee moves continuously in practice, static values are difficult to measure during movement. Attempts to correct the dynamic peak values to a static value are challenging: the sensor does not have time to stabilize during repeated movement, and filtering can only partially determine the actual angle. Therefore, it is more practical to use the dynamic values for real-time monitoring.

#### Limitations of dynamic measurements

The dynamic measurements do reveal some points of concern:

- The deviations increase at high and low angles (<20° and >100°), limiting the accuracy during full flexion and extension.
- The speed of movement affects the measured resistance: higher speeds result in higher peak values.
- The starting angle of the movement also has a slight impact on the measured resistance values.

Due to these factors, it is not possible to reliably measure the exact knee angle during moving bends right now. For accurate angle determination, the sensor is therefore limited to the 20–100° range, where a rough indication of the angles is possible.

### Possibilities for rehabilitation

Despite its limitations, the knee sensor band still offers several practical advantages:



#### Monitoring of movements and estimated angles

The dynamic sensor values show how often the knee is bent and extended during exercise sessions. This can help objectively monitor adherence to therapy and activity level. Although the angle cannot be determined precisely, an estimation can be made.



#### Indication of intensity, speed and consistency of movement

The peak values and the dynamic resistance pattern provide an indication of the speed and force of movement. This allows the physical therapist to determine, whether a patient is performing exercises consistently and at the correct intensity. Changes in speed and intensity can indicate recovery, but also overload or compensatory behaviour.



#### Trend measurements and progress

Even if precise angle values are difficult to determine, relative changes over time will be visible and can be tracked: more or less movement, larger or smaller knee bends, longer ranges of motion, etc.



#### Asymmetry: difference between left and right

Although the knee flexion angle cannot be determined accurately and reliably under all circumstances, the sensor sleeves do allow for the detection of ROM symmetry between the left and right knee. Differences in timing, speed, and intensity of movement can be analyzed. This allows for the detection of asymmetry in movement, like a delayed movement on one side.

### Indicative representation of knee flexion

Based on the deviations between the measurement cycles, it can be concluded that the measured knee angle has a margin of error of approximately 5°. This means that the actual knee angle may be 5° higher or lower than the measured value. Figure 106 shows the average resistance value per 10 degrees, with the blocks showing the maximum measured deviations.

To be transparent about the limited accuracy and to avoid apparent precision, knee angles have been represented in 10-degree increments: 10, 20, 30, 40°, etc. Stating specific values, like 62 degrees, would suggest a degree of accuracy that the sensor cannot guarantee based on the validation test. For example, if a resistance value of 90 Ω is measured, it will be mentioned in the overview after a session as an 80-degree knee angle. The live graph also displays only values per 10 degrees on the y-axis. From 95 Ω, >100° is currently displayed because angles above 100° have overlapping resistance ranges.

This representation should clarify that the knee sleeve does not give exact angle measurements, but an estimation within a certain range. At the same time, it remains possible to visualize changes, trends, and progress in knee flexion without users relying too much on the apparent accuracy of individual measurements.

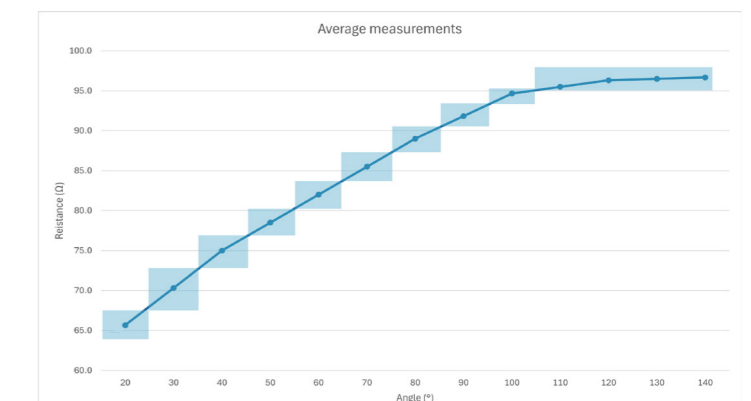


Figure 106. The 10-degree interval by adding a range per 10 degrees. The overlapping range from 100 to 140 degrees shows that the 10-degree interval is not possible for angles from 100 degrees

## 13.4 Work range check

To explain the sensor's flattening, an additional test was performed. During previous tests, the sensor was evaluated at a strain of 35%. However, Figure 104 showed that the sensor stretches to approximately 50% at maximum flexion (140°). The original hypothesis was that the sensor has a working range of <40%, which would explain the flattening starting at approximately 100°.

To investigate this, the sensor was retested at 50% strain. However, Figure 107 shows a linear curve, indicating that the sensor's working range is at least 50% and therefore large enough. Therefore, the signal flattening after 100° appears not to be caused by a limited working range of the sensor.

Another possible explanation for the flattening of the sensor response is the influence of the sensor's length. Although the sensor is loaded with the same percentage strain, the absolute length can affect the stress and strain distribution within the conductive yarn, which can influence the electrical response. Due to the limited height of the LETT meter, it was not possible to stretch a 14cm sensor by 50% so this tests could not be performed.

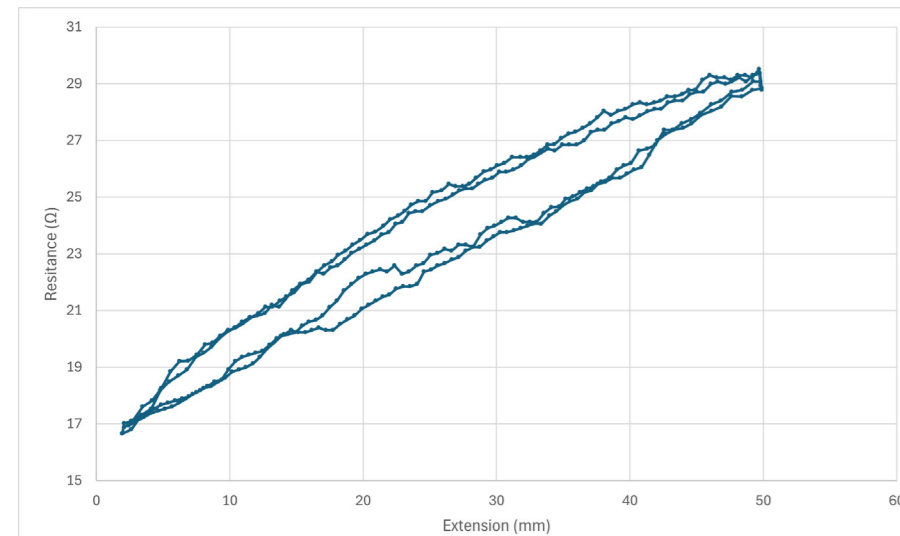


Figure 107. Two stretch cycles up to 50% stretch showing a linear performance graph

## 13.5 Discussion and conclusion

### Discussion

When interpreting these results, a few limitations must be taken into account. The measuring setup was constructed by hand, which meant that the knee angles could deviate by up to a maximum of 2°. However, this does not constitute a significant limitation for the validation test, as the set angle was consistently repeated within and between measurement cycles. This allowed the repeatability of the measurements to be properly assessed.

In addition only three cycles were performed for both the static and dynamic measurements due to the limited project time. The limited number of cycles may influence the results: in the dynamic measurements for example, the lines of the three consecutive cycles were slightly above each other, but it is unclear whether this represents a gradual increase in resistance over consecutive cycles or if it is coincidental (Figure 103). More cycles could show whether the resistance keeps changing slowly or gets stable, thereby enabling more robust conclusions.

Despite these limitations, the consecutive knee bends within a single cycle were very reproducible. This means that consecutive bends within an exercise can be reliably compared. Based on this, statements can be made about the consistency of movements, while absolute angle values are less accurate.

Another limitation of the validation test is that it was performed with only one knee. Anatomical differences between knees, such as size and shape, can affect the sensor output (as discussed further in X). The resulting variations in absolute resistance values per knee were not a primary focus of this test, as the validation test primarily focused on the sensor's repeatability. However, further research using multiple knees is needed to determine the extent to which these measurement patterns across different knee angles vary between different anatomies and what this means for the calibration and interpretation of the measurements.

### Conclusion

The static measurements show that the strain sensor in the knee sleeve provides reasonably stable and reproducible results at fixed knee angles in the range of 20° to 100° knee flexion. In this range, the deviations between repeated flexions and after repositioning are limited to approximately 1Ω, making this range suitable for monitoring (RQ 1).

During dynamic knee flexion, the measured values clearly deviate from the static values due to the peak values that occur during dynamic flexion. The knee flexions within a cycle are virtually identical, while there is a maximum deviation of 2Ω between the measurement cycles (RQ 3). In addition, both the speed of movement and the starting position of the knee influence the measured resistance: higher speeds and larger preliminary flexion angles result in higher measured values (RQ 2).

In this study, it was decided to use the dynamic measured values for monitoring, because they are representative of measurements during active movements and also show a larger and clearer change in resistance (RQ 2).

Due to the small deviations in the measurements, accurate angle determination during movement is not reliable, especially for angles smaller than 20° and larger than 100° (Research question 4). However, the sensor is suitable for indicative angle estimation, movement detection and trend analysis during rehabilitation.



Figure 108. The angles had small deviations up to a maximum of 2°

# TAKEAWAYS & RECOMMENDATIONS

## Key takeaways

### Sensor behavior and sensitivity

- The strain sensor is most sensitive and reliable between 20°–100° of knee flexion. The accuracy decreases at the extreme angles (<20° and >100°).
- Dynamic measurements show higher resistance peaks than static measurements because of viscoelastic effects and internal tension in the textile.
- The sensor response is influenced by the movement speed and starting position, which can be explained by hysteresis.



## Recommendations

- Focus monitoring and calibration within the mid-range. The sensor needs to be improved for measuring at the extreme angles.
- Use dynamic measurements for monitoring, rather than attempting to convert them to static angles.
- Additional research is needed in speed and movement influences

### Reproducibility and repeatability

- Repeated cycles within a session and after repositioning show small deviations (0–2°), indicating sufficient repeatability for rough angle estimation in mid-range angles.



- Emphasize consistency over absolute accuracy in the application and inform users that exact angles are approximate (~5° margin).

### Work range and mechanical factors

- The sensor can be stretched at least 50%, so signal flattening beyond 100° is not because of a limited work range but may be affected by sensor length and strain distribution on the knee.



- Additional research is needed to examine the influence of the knee on flattening of the signal, considering length and strain distribution.

### Applicability for rehabilitation

- Although precise angle measurement is limited, the sensor sleeve can track:
  - Movement frequency and repetitions
  - Relative range of motion and trends over time
  - Speed, intensity, and consistency of exercises
  - Symmetry between left and right knee
- Giving knee angles in 10-degree increments avoids misleading precision while still showing meaningful progress.



- Use sensor data for objective feedback, monitoring adherence, and detecting asymmetries, rather than exact angle reporting.

### Test limitations

- The hand-made test setup and single-knee testing introduced small deviations, but overall repeatability was sufficient for validation purposes.



- Future studies should include multiple participants to evaluate anatomical variation and support calibration across users.



Figure 109. The main part of the user test has been performed at Roelfsma fysiotherepy (Roelfsma Fysiotherapie, n.d.)

## 14. User test evaluation

This chapter discusses how the user tests were conducted, the insights and improvements that emerged from these tests, and the conclusions that can be drawn from them.

- 14.1 Testing plan and pilot
- 14.2 PT evaluation
- 14.3 Patient evaluation
- 14.4 Extra participants
- 14.5 Discussion and conclusion

### 14.1 Testing plan and pilot

Testing and evaluation plays a important role in the concept's development. The tests were conducted in a realistic context, together with a physioical therapist and a patient. This proved to be very valuable, since testing in a practical setting provides direct insight into actual use, user experience, and potential areas for improvement from stakeholders who will be using the product in practice.

To gain a broader picture and compare different opinions and experiences, additional tests were conducted with three individuals from a different age group. These test subjects are master's students at the Faculty of Industrial Design Engineering. Although they have no experience in rehabilitation, they are trained to critically examine designs and identify improvements. This allowed for the collection of diverse perspectives, and the questions also stimulated discussion, leading to valuable insights.

#### Testing plan

The purpose of the test is evaluating on

##### For the patient

- Comfort of the knee sleeve (feel, wearability, irritation)
- Fit and stability (does the sleeve stay in place)
- User-friendliness and clarity of the interface
- Comprehensibility of the information shared
- Perceived added value of continuous knee measurement during rehabilitation
- Motivation and confidence through insight into progress
- Areas for improvement or additional requirements

##### For the physical therapist

- Relevance and usability of the measured data
- Clarity and transparency of the interface
- Integration into current practice
- Added value of the knee sleeves
- Areas for improvement or additional requirements

##### The main research questions of the test are

1. Do patients and physical therapists understand what the knee sleeve measures and what the data means?
2. Is the interface perceived as clear, logical, user-friendly and motivating?
3. Is the knee sleeve comfortable and stable during exercises?
4. Is the system seen as a valuable addition to the rehabilitation process?

##### Patient test

The patient test consisted of the following components:

- Introduction  
The participant received an explanation of the function and purpose of the knee sleeve, while the product was shown. They were also asked what type of knee complaint they had and how long they had been in rehabilitation.
- Phase 1: Live graph  
First, the first part of the interface was shown and explained. This included logging in, connecting the knee sleeve, and filling in exercises. The participant was then asked to put on the knee sleeve. While performing the exercise, the live graph and its associated functionalities were explained. Questions were then asked about their experience of this graph and the knee sleeve, as well as their general opinion.
- Phase 2: Post-Exercise Information  
Next, the part of the interface that displays post-exercise information was discussed. The participant's opinion on this was gathered using targeted questions.
- Phase 3: Long-Term insights  
Finally, the long-term overview graphs and visualizations were shown. Again, the participant was asked for their opinion and interpretation of the information.
- Conclusion  
After showing and discussing the entire concept, additional and more general questions were asked to gain a complete picture of the participant's experience.

## 14.2 PT evaluation

### Physical therapist test interview

The physical therapist was guided through the entire interface, intended for both the patient and the physical therapist. He was asked to make comments directly during the demonstration, and specific questions were asked during the explanation of the interface. General questions were asked after the explanation.

A detailed testing plan can be found in appendix F.

### Pilot test

To evaluate the test plan's flow, duration, and comprehensibility of the questions, a pilot test was done with a student within the faculty of Industrial Design Engineering.

Based on this pilot, some adjustments were made. The order of the test was changed to make it more logical and understandable for the patient. For example, it proved more effective to first demonstrate the live graph and then explain the information the knee sleeve collects and the insights it can provide.

In addition, due to time constraints, it was decided to explain the knee sleeve's functions and interface instead of asking participants to interpret them themselves. This allowed for focus on their experience and opinions.

Finally, the number of questions was shortened, and some were reformulated because the original amount was too big and some were expected to be difficult for the patient to answer.

This section focused primarily on the questions about the interface and the functionalities of the knee sleeve that are relevant to the physical therapist.

In addition, questions were also asked about expected patient reactions and opinions, as only one patient could be interviewed. The physical therapist has a good understanding of how patients usually behave and react to the measurements currently being taken, making their insights valuable for evaluating the interface and the product.

### Vision on the knee sleeve within rehabilitation

The interviewed physical therapist considers the knee sensor sleeve as valuable and accessible addition to the current rehabilitation process after knee surgery and knee injuries. While current practice often involves snapshots with a goniometer or subjective observation, the knee sleeve offers the possibility of continuously, objectively, and repeatably measuring movement.

The biggest added value of the concept is the combination of measurement and exercise. The physical therapist can directly observe how the knee moves during exercises and how this movement develops over time. This makes the knee sleeve besides a measurement tool a feedback tool that can support the rehabilitation process as well.

### Phase-oriented use

The interview showed that the knee sleeve is particularly relevant in the early stages of rehabilitation. In the first and second phase, directly after surgery or trauma, the focus is on regaining range of motion. In these phases limited mobility, compensatory behavior, and clear differences between the left and right leg often occur. The knee sleeve can give insights by objectively visualizing these differences.

In later phases of rehabilitation, where the focus shifts to sport-specific and strength training, measuring range of motion is less relevant. In these phases, range of motion has often already been regained and other performance indicators play a bigger role. Therefore, the interface and data visualization must be tailored to the early rehabilitation phases.

### Sensor placement and measurement reliability

An important consideration when using the knee sleeve is sensor positioning. The physical therapist emphasizes that the absolute degree value is less important than consistent measurements on the same person. Due to anatomical differences, such as the position of the kneecap, measured angles will vary from person to person. As long as the sensor is positioned consistently for each measurement, comparison over time is possible. The reference circle on the kneecap is mentioned as a strong design choice because it helps the patient correctly position the sleeve.

It also becomes clear that measurement errors are a significant limitation. A measurement error of approximately 5 degrees, as with the current prototype, is considered too large to make reliable statements. For future development, a maximum measurement error of 2,5 degrees is considered desirable.

In practice, patients usually wear tight clothing, such as leggings or shorts, during treatments, allowing measurements to be taken on or close to the skin. However, the physical therapist emphasizes that it is okay to be proactive in this regard.

### Datavisualisation and live feedback

The live graph with a line for the left and right leg is considered a powerful way to visualize movement. Adding a target line/plane for a desired flexion angle, helps patients understand what they are working towards and increases motivation during practice. The ability to scroll through the graph afterward is valuable for visualizing changes within an exercise series, such as reduced compensation or improved symmetry.

At the same time, it was mentioned that feedback during the exercise itself should be used cautiously. Constant warnings about asymmetry can be demotivating in the initial phase. Feedback after an exercise, in the form of a short overview or positive feedback, is considered more effective. This supports learning without interrupting the practice process.



Figure 110. Roelsema Fysical therapie practice

## Measurements

Asymmetry between the left and right leg is considered one of the most important parameters in knee rehabilitation. Showing asymmetry as a percentage is considered clear and understandable, if it is well explained.

In addition, consistency of movement is considered a valuable metric as well. Consistency reflects control and stability in exercise execution and can help patients get insight into their movement quality.

The concept of “intensity” is considered complex and previously misinterpreted within this project. Intensity in physical therapy is very context-dependent and depends not only on the flexion angle and speed of movement but can also be linked to strength, weight, or even heart rate. The interview shows that adding intensity measurements would unnecessarily complicate the system and potentially detract from the core function of the knee sleeve.

## Comprehensibility of metrics and engagement

The interview with the physical therapist reveals that many patients, especially those intensively engaged in their rehabilitation, are familiar with terms like asymmetry and consistency. Younger and athletic patients, in particular, are often actively involved in their recovery and actively monitor their progress. They generally know the required values for tests performed after three, six, nine, and twelve months. The physical therapist indicates that these patients are not only willing to review the data but also understand what this information means.

According to the physical therapist, patients are used to working with measurements and performance goals during their rehabilitation. This creates a clear expectation: patients want to know where they are, what they are working towards, and whether they are on track. Making progress visible, for example, in the form of graphs or percentages, aligns well with this need.

## Subjective feedback and badges

Adding a subjective score, by which the patient indicates how they experienced the exercise or how much discomfort they experienced, is considered very valuable. This self-report gives context to the objective data and can lead to deeper discussions between the patient and physical therapist. Especially when objective measurements and subjective experiences do not match, relevant information emerges.

In addition, motivational elements such as badges after an exercise are considered supportive. The knee sleeve then serves not only as a measurement tool but also as a tool to increase adherence, especially when exercising at home.

## Home use and sense of security

The option to give the knee sleeve home is considered as a big advantage. It encourages patients to exercise independently and provides the physical therapist with insight into their exercise habits outside the practice. In addition, the sleeve can give a sense of safety and security, especially in the early stages when patients experience instability. This psychological effect contributes to confidence in movement and recovery.

## Prerequisites for successful implementation

Finally, the physical therapist mentioned that the success of the knee sleeve depends on clear instructions for both patients and physical therapist. Consistent placement, explanation, and reliable sensor technology are important to minimize measurement errors. Affordability also plays an important role: the sleeve should have a low price when purchased individually, while a higher price is more acceptable in practical settings.

# 14.3 Patient evaluation

## Patient background and rehabilitation process

The interviewed patient (Table 17) has a completely torn anterior cruciate ligament (ACL) but has not undergone surgery. In consultation with the orthopedist and physical therapist, a conservative rehabilitation program was chosen, partly due to the patient's age and the type of work and sport he participates in.

The patient has been in rehabilitation for approximately six months. Although full knee flexion is not yet possible, he is experiencing clear progress. At the same time, the vulnerability of the recovery process becomes clear: “If I don't exercise for a while, like around Christmas, I immediately notice it getting worse.” This mentions the importance of consistent exercise and insight into progress during a long-term rehabilitation program.

## Objective data and insights

The patient indicates that he finds it very valuable to have insight into his knee movement. Viewing objective data about his movement and progress gives him better insight into how his recovery is progressing and where improvements can be made. This insight not only helps him understand his own recovery but also supports his confidence in the rehabilitation process.

The patient showed interest in checking the collected information and mentioned finding measurements like consistency and asymmetry understandable and relevant.

	Background	Gender	Age
Patient Physical therapy practice Roefsema	Torn anterior cruciate ligament	Male	±45

Table 17. Patient information



Figure 111. The patient is performing a squat exercise while the live graph shows his movement

### Experience with comfort and wearability

Looking at comfort, the patient finds the knee sleeve comfortable and non-restrictive during movement. Although the sleeve feels somewhat tight, this seems do to the small size of the sleeve minor swelling in the knee. The sleeve does not restrict movement, which is important for long-term use during exercises.

The patient does not feel the electronics on the outside of the leg. This confirms that the positioning of the electronic components does not negatively impact comfort.

### Value of long-term insights and progress

The patient values being able to track his progress over a longer period of time. The rehabilitation process is experienced as long and intensive, making it motivating to see an upward trend in performance: "You don't notice it every day, but when you see it over a longer period, you can see that things are improving." Seeing progress over weeks or months confirms that the efforts are effective, even when changes are less visible day to day.

### Planning exercise sessions

In addition, an overview of exercise days in a calendar is considered useful. The patient partially tracks his exercises himself in a diary, but sees added value in an automatically generated overview that shows which exercises have been done, for how long, and how often. This gives some reflection and makes it easier to recognize patterns in exercise behavior.

The patient also mentioned having an irregular work schedule, which makes fixed exercise days not always feasible. The ability to schedule exercise sessions weekly fits well with his lifestyle.

In addition to exercising in the practice, the patient also practices independently in a fitness room at work or at home. This mentions the value of a system that is not only usable within the practice but also gives support for independent exercising at other locations.

### Support for independent practice

The patient likes the knee sleeve as a tool when a physical therapist is not present. The sleeve can give guidance during independent practice outside the practice. He also appreciates that the physical therapist can monitor progress remotely.

The patient sees the knee sleeve and its interface as an extension of the physical therapist: a tool that provides support outside the practice, but can also provide additional depth during sessions in the practice. This reinforces the feeling of continuity in guidance. "Then you know someone is watching, even if you're practising alone."

### Motivation and gamification

Motivational elements such as badges, levels, or rewards are positively received by the patient. The patient indicates that he already uses these types of systems, for example, through his sports watch, and finds them stimulating. While not every user would like this, gamification can provide additional motivation for some patients to continue exercising consistently.

The patient mentions that such elements work particularly well with the "right person," suggesting that personalization and optionality are important when designing motivational features.

## 14.4 Extra participants

### Live graph while moving

All participants (Table 17) thought the live graph is interesting and motivating. Being able to see the movement in real time helps users better understand what they are doing at that moment and how their knee is moving. Working with a target line was particularly valuable, as it gives a concrete reference point during practice.

One suggestion for improving the graph was to add a clear visual confirmation when the target angle is achieved, for example, by coloring the target line green as soon as the graph rises above it. This makes it directly clear that the flexion reached the target angle, without additional text or explanation that distracts.

In addition, one participant expressed interest in reviewing previous bends within an exercise. Showing multiple "waves" simultaneously can distract from the current movement, but being able to zoom out after the exercise to view all performed repetitions side by side was found interesting. Scrolling or zooming out provides insight into patterns, such as fatigue or improvement within a set, which contributes to reflection on the quality of the exercise.

Regarding feedback during movement, participants mentioned that short, visual cues are desirable; minimal feedback that is supporting without the need of completely focusing on the screen. This keeps the attention on the movement itself while still receiving feedback.

Nr	Gender	Age	Experience in smart wearable
Participant 1	Female	23	Yes, in possession of sports watch
Participant 2	Male	21	No
Participant 3	Female	23	No

Table 17. Participant information



Figure 112. The participant is performing a squat exercise while the live graph shows her movement

Looking at the evaluation after exercises, one participant mentioned that a single general score, such as “how did it go?”, lacked nuance. She indicated that an exercise can be performed technically well, while at the same time experiencing pain or discomfort. This allows a single score to have multiple meanings, which can be confusing. Based on this, it was considered valuable to add multiple forms of subjective feedback, such as a separate score for how well the exercise felt performed technically, a score for pain or discomfort, and possibly a score for how someone feels afterwards. Several participants also mentioned adding a text box, allowing users to add specific comments. This context can help improve the interpretation of the measurement data and enable communication with the physical therapist.

### Wearing experience and use

Wearing the knee sleeve was experienced positively. The sleeve stays securely in place during exercises and doesn't restrict movement. Although some participants described the sleeve as a bit tight, this did not bother them.

One participant did mention that the fabric of the sleeve felt slightly warm. This wasn't immediately perceived as a problem, but it is something to consider for long time use.

In addition, the visual lines on the sleeve were helpful, clearly indicating that these lines should run straight across the knee. Participants also indicated that they could barely feel the electronic components while moving.

### Information after the practice session

The information displayed after a practice session was also found valuable by the participants.

One participant suggested that more emphasis could be placed on the measured values, with numbers displayed large and clearly in information blocks.

Not all participants immediately understood the terms used, such as asymmetry and consistency, although these concepts were considered interesting in their content. Therefore, one participant suggested adding an information icon next to these terms where additional information could be found: what the term means, how it is measured, and does value represent.

### Long-term insights: progress and agenda

Participants found the visualization of progress over a longer period, like the monthly graphs, clear and motivating. Being able to see an upward trend over several weeks or months confirms that recovery is progressing and that effort is having an effect.

Adding a goal to the graphs was also mentioned as an interesting and motivating addition. Although setting goals that are too high in the early stages can be demotivating, setting goals for each stage could be helpful.

The calendar functionality was also considered a valuable addition because of the overview of activity and the ability to schedule exercises. An overview of when exercises were performed, which sessions were completed, and which were missed also helps users structure their rehabilitation.



Figure 113. The participants shares her understanding and opinion about the interface

## 14.5 Discussion and conclusion

### Discussion

When testing the knee sleeve, several limitations of the study must be taken into account. The number of participants was limited: only one physical therapist was involved, one patient who was actually undergoing knee rehabilitation, and three students participated as simulated patients. In addition, the testing took place within a single practice; other practices may work differently, which means that the experiences and needs of physical therapists there may differ.

The physical therapist and the patient provided valuable insights into the use of the knee sleeve and the interface within a realistic rehabilitation context. The three students helped to supplement the limited patient experience, but their perspective was different. They have no experience with knee rehabilitation and were, for example, less familiar with terms like asymmetry and consistency, which were considered important and understandable by the patient and physical therapist. As a result, their feedback may be less representative of the target group of patients undergoing rehabilitation.

However, this combination of participants offered advantages. Testing with a physical therapist and a real patient gave practical insights, while the design students offered a critical view of ease of use, interface, and overall user experience. Together, this gave valuable, complementary feedback for the further development of the knee sleeve.

### Conclusion

Based on tests and interviews with the physical therapist, the patient, and several participants, it can be concluded that the knee sleeve offers clear added value in the early stages of knee rehabilitation. The concept aligns well with the need for objective, continuous measurements of knee movement, in contrast to current practice, which primarily relies on snapshots and subjective observations (RQ 4).

# TAKEAWAYS & RECOMMENDATIONS

The biggest strength of the knee sleeve is its combination of measurement and practice. The live visualization of the knee flexion, with separate lines for the left and right legs and a clear target line, is seen as insightful and motivating (RQ 2 and 4). Measurements like range of motion, asymmetry, and consistency fit the focus of the early rehabilitation phases and are considered relevant and understandable by both the physical therapist and patient (RQ 1). Visualizing the progress over time also adds value, especially during long-term rehabilitation (RQ 4).

The knee sleeve is also seen as a valuable tool for independent practice outside of the practice. The ability to share data with the physical therapist strengthens the sense of guidance and continuity (RQ 4). The comfort of the sleeve and the positioning of the electronic components were experienced positively (RQ 3). The visual lines and reference point on the kneecap support correct use (RQ 2 and 3).

At the same time, the results indicate that further development is necessary. Measurement accuracy is the most important concern: a measurement error of approximately ten degrees is considered too large for clinically reliable interpretation (RQ 1 and 4). In addition, the interface needs clear explanations of the terms used so that all users can interpret the data correctly (RQ 1 and 2).

Excessive or continuous feedback during exercise can be demotivating, while post-exercise feedback and short visual confirmations are more in line with the learning process. Adding subjective self-reports, such as pain or perceived quality of the exercise, is considered a valuable addition to the objective measurements. Measuring “intensity,” on the other hand, is considered less relevant (RQ 4).

In summary, this study shows that the knee sleeve is a promising and a user-friendly innovation for early-stage knee rehabilitation. With improvements in measurement accuracy, instruction and data visualization, the system can develop into a valuable tool that supports the rehabilitation process of patients (RQ 1-4).

## Key takeaways

Added value for early-stage rehabilitation

- The knee sensor sleeve is most valuable during the early stages of rehabilitation, when range of motion (ROM), asymmetry, and movement consistency are the most important.
- Both the physical therapist and patients perceive it as a meaningful addition to traditional methods.

Motivation & engagement

- Live graphs, target lines, and progress visualizations motivate patients and improve understanding of their performance.
- Gamification elements like badges were positively received by the participants.

Comfort & wearability

- The sleeve is comfortable, minimally restrictive, and the electronics are barely noticeable.
- Visual reference lines on the knee help users correctly position the sleeve.

Sensor limitations

- Current measurement accuracy ( $\sim 5^\circ$  error) is insufficient for clinically reliable interpretation. However, absolute values are less critical than trends
- Consistent sensor placement is important

Feedback strategy

- Excessive or continuous feedback during exercises can be demotivating. Feedback after exercise and short visual cues during movement are more effective for learning and motivation.

Support for independent practice

- The sleeve supports patients during home exercises and allows therapists to monitor performance remotely.

## Recommendations

- Further development of the sleeve and interface should focus on the early rehabilitation stages.

- Optional gamification elements (badges, levels) and simple, intuitive live feedback should be included. Simple visual cues during exercises and summary feedback afterward should be used to support motivation without distraction.

- The current textile design and positioning cues should be maintained. Future iterations should ensure comfort remains for extended use.

- Sensor accuracy and placement consistency (aim for  $\pm 2.5^\circ$ ) needs to be improved. It should be clearly communicated that the sleeve is intended for trend analysis and indicative progress rather than precise angle measurements.

- Visual cues during exercises (e.g., color change when a target angle is reached) should be used and a concise summary afterward should be provided with progress tracking.

- Clear instructions need to be provided and simple workflows for home use. Automatic data sharing with the therapist should be enabled to track progress outside the clinic.



Figure 114. The concept being evaluated

# 15. Concept evaluation

In this chapter, the concept is evaluated by assessing the extent to which the design requirements have been met and by reflecting on the desirability, feasibility, and viability of the concept.

- 15.1 List of requirements
- 15.2 Desirability
- 15.3 Feasibility
- 15.4 Viability

## 15.1 List of requirements

This chapter revisits the list of requirements and evaluates the degree to which they have been fulfilled, as well as identifying remaining challenges and concerns.

- Fulfilled
- Remaining concerns

### 1. Functional requirements (sensor)

These requirements were evaluated using the experimental research and evaluation tests.

Nr.	Requirement	Specification	Evaluation
1.1	Knee flexion measurement range	The sensor must be able to measure a knee angle between 0°–130°. In other words, the sensor must still be operational at 50% elongation.	Controlled tests showed that the sensor itself remains operational up to 50% extension, meeting the requirement. However, when integrated into the knee sleeve, the effective working range was limited to approximately 100° of knee flexion. This indicates that the placement and interaction of the sensor with the knee and textile sleeve influence the functional range. Further research is needed to optimize sensor placement and integration to achieve the full intended knee angle range.

Table 18. Functional requirements evaluation

1.2	Sensitivity	The gauge factor must be at least 1.	Controlled testing showed that the sensor has a gauge factor of 2.27, exceeding the requirement. When integrated into the sensor sleeve, the gauge factor decreased to 0.95. Although this value is close to the required value, it does not fully meet the requirement. Additional research is needed to determine how the sleeve affects the sensor sensitivity.
1.3	Linearity	The linearity must be at least 95%.	The controlled test showed the a linearity of 96%, which is sufficient.
1.4	Hysterese	The hysteresis may be a maximum of 20%	The controlled test showed a hysteresis of 16.31% and thus does not exceeds the maximum and therefore meets the requirement.
1.5	Repeatability	The repeatability may not exceed 1%.	The controlled test showed repeatability of 0.43%, which is below the maximum allowed value and thus meets the requirement.
1.6	Skin contact and anatomical fit	The sensor must lie snugly against the skin to follow the anatomy of the knee during flexion and extension without slipping.	During the user tests, the sensor lays snugly against the skin and remained in position during knee flexion and extension, indicating that the requirement is met.
1.7	Movement with the knee	The sensor must be securely attached at the top and bottom.	The sleeve stayed well in place during movement during the user test, indicating that the requirement is met.



Figure 115. The on button of the sleeve and its indicating led

## 2. User comfort, ergonomics and appearance (sleeve)

These requirements were evaluated using the user evaluation tests.

Nr.	Requirement	Specification	Evaluation
2.1	Ease of use	The sleeve must be able to be put on or taken off in <1 minute by a user with limited mobility.	The user evaluation tests showed that participants were able to put on and take off the sleeve within approximately 30 seconds, meeting the requirement.
2.2	Comfort duration	The sleeve should remain comfortable for at least 1 hour of continuous wear when exercising without irritation, pinching or pressure points.	During user evaluation tests, the sleeve was worn for a maximum of 30 minutes. Although participants reported the sleeve to be comfortable and unobtrusive during movement, additional testing is needed to confirm comfort over a full hour of use.
2.3	Range of motion comfort	The sleeve must not noticeably restrict the movement of the knee, including deep flexion and full extension.	Participants reported that the sleeve did not restrict movement and felt unobtrusive during flexion and extension, indicating that the requirement is met.
2.4	Light-weight design	The sleeve must be lightweight so that wearing it does not hinder activities or exercises.	Participants did not report the sleeve as feeling heavy during use. Some participants noted that the sleeve felt slightly tight, but this did not hinder movement, indicating that the requirement is met.
2.5	Soft and skin-friendly inner surface	The inner surface of the sleeve must be made of soft, skin-friendly materials that prevent chafing or irritation during movement.	Participants did not report irritation or chafing during movement. The sleeve remained in place during use, reducing friction and supporting skin comfort.

2.6	No sharp of pointy components	The sleeve must not contain any sharp or pointy components that could cause discomfort, pressure points, or injury.	All components are smoothly integrated into the sleeve and covered with an additional fabric layer, providing enough protection, indicating that the requirement is met.
2.7	Breathability and Moisture Management	The sleeve must be breathable and capable of regulating moisture to minimize heat buildup and perspiration.	The fabric was generally perceived as breathable. However, two participants mentioned that the sleeve felt slightly warm during use, indicating that breathability could be further improved.
2.8	Stable fit	The sleeve should not shift during activities or exercises.	The sleeve stayed well in place during exercises, meeting the requirement.
2.9	Donning guidance	The sleeve must include visible markers or orientation indicators, to show how the sleeve should be put on correctly.	The sleeve contains visible markers that support correct placement of the sleeve, meeting the requirement.
2.10	Fitting appearance	The sleeve should have an neutral appearance with a colour/design touch	The sleeve has a black base colour perceived as a neutral (x.x Aesthetics) combined with blue accents. Participants perceived the design as visually appealing.

Table 19. User comfort, ergonomics and appearance requirements evaluation

### 3. Technical and electronic requirements

These requirements were evaluated using general checks and the user evaluation tests.

Nr.	Requirement	Specification	Evaluation
3.1	Battery life	The battery should last at least 1 hour of continuous use. Preferably longer for multiple sessions.	The 500 mAh battery lasted approximately 8 hours of continuous use, supporting multiple sessions without recharging. With further optimization of energy efficiency, battery size could be reduced while maintaining this usage time.
3.2	Standardisation & safety	Electrical components and conductive yarns should be standardised and certified, ensuring safety and scalability.	All electrical components and conductive yarn are certified and commercially available, meeting the requirement.
3.3	Compact electronics	The electronics must be compact and lightweight so it doesn't disturb the user during movement.	Participants reported that the electronics were unnoticeable during movement, indicating that the requirement is met.
3.4	Secure mounting	The electronic components must be securely attached and protected so they cannot shift, detach, or get damaged.	The combination of an unstretchable fabric layer and a leather pouch securely held the electronics in place during tests.

Table 20. Technical and electronic requirements evaluation

3.5	Electronics protection	All electronic components must be protected with suitable encapsulation to prevent damage.	The leather pouch provided protection against impacts and point loads, meeting the requirement.
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### 4. User Interface requirements

These requirements were evaluated using general checks and the user evaluation tests.

Nr.	Requirement	Specification	Evaluation
4.1	Multi-Interface system	The system must provide two distinct user interfaces: a real-time interface and progress-overview interface for patients, and a clinical dashboard for healthcare providers.	The system includes two interfaces: a patient interface with real-time graphs, session overviews, progress overviews, and badges, and a physical therapist interface with session and progress overviews. The physical therapist can export progress data to occasionally share with the orthopedist.
4.2	Clear and simple navigation	All interfaces must provide intuitive navigation with minimal steps required to access key information.	Based on prior interface research, the interface uses clear page separation per topic, progressive disclosure, and a combination of color, icons, and graphs to support intuitive navigation. During the user evaluation, participants described the interface as clear and well-structured, and mentioned that key information was easy to find with minimal effort. This indicates that the requirement is met.

4.3	Low cognitive load	The real-time interface must avoid complex metrics and present only helpful information during exercises.	Participants described the real-time graph as clear and non-distracting, allowing them to focus on their movements while still receiving useful feedback.
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Table 21. User Interface requirements evaluation

### 5. Sustainability and maintenance requirements

This requirement was evaluated using a general check.

Nr.	Requirement	Specification	Evaluation
5.1	Replaceable components	Sensor and electronics must be removable and replaceable without requiring full reconstruction of the sleeve.	A damaged sensor can be unstitched and replaced with new conductive yarn, and the electronics can be replaced by opening the leather pouch, meeting the requirement.

Table 22. Sustainability and maintenance requirements evaluation

### Conclusion

The evaluation shows that most of the requirements have been met. However, some requirements need further optimization to fully meet the criteria. These are further discussed in the recommendations section.

## 15.2 Desirability

The desirability of the concept was evaluated by reflecting on the extent to which both the physical therapist and the patient consider the use of the knee sensor sleeve and interface desirable within their rehabilitation context. The user test showed that both stakeholders recognize the added value of the concept and see it as a relevant addition to existing working methods.

For the physical therapist, the concept meets the need for objective and repeatable information without unnecessarily complicating the workflow. The ability to combine measurements with exercises and compare them over time is seen as useful in the early stages of rehabilitation. This increases the willingness to actually use the system in practice.

For patients, the concept fits well with the experience of a long-term and intensive rehabilitation process, in which continuity and independence are important. The possibility of receiving support outside the treatment practice contributes to the acceptance of the system as part of the recovery process. In addition, the concept is not perceived as burdensome or disruptive, which is important for voluntary and long-term use.

In summary, the evaluation shows that both physical therapist and patient find the concept desirable and that it sufficiently meets their expectations, working methods, and motivation to actually use it.

## 15.3 Feasibility

The controlled tests, validation tests, and user tests that were carried out showed that the concept of the knee sleeve is, in principle, technically feasible for its intended use. The combination of a textile knee sleeve with an integrated stretch sensor and an interface that presents the measurement data in a clear manner functions as a coherent system.

### Sensor performance

Under ideal laboratory conditions, the sensor performed well, with high sensitivity (gauge factor 2.27), high linearity (0.96), good repeatability (0.43%), acceptable hysteresis (16.31%), and a working range of up to 50% extension. When the sensor was integrated into the knee sleeve and applied to the knee, the sensitivity decreased (gauge factor 0.95) and the working range appeared to be limited to approximately 100° (about 40% extension).

The hysteresis of the integrated sensor (16.60%) remained comparable to that measured under laboratory conditions (16.31%). The linearity and repeatability of the sensor in the knee sleeve could not be reliably determined under conditions of use, as the knee cannot move in exact and reproducible angles.

### Sensor usability

The validation test showed that the sensor maintained a consistent resistance pattern during repeated use and after repositioning of the knee sleeve, with a maximum deviation of 2 ohms. Based on this, knee movement can be roughly estimated in steps of approximately 10 degrees, i.e., with a margin of error of 5 degrees. However, this accuracy is insufficient to make clinically reliable statements about absolute knee angles, for which a margin of error of no more than 2-3 degrees is considered acceptable. The current prototype version is therefore not yet suitable for accurately determining knee angles in degrees.

However, it proved to be possible to reliably measure parameters such as the number of bends and the consistency of movement. These are based on relative differences within a single session, which proved to be repeatable in the validation test.

Accurate asymmetry measurements in movement between the left and right knee are not yet possible. The small deviations in the sensors in the two knee sleeves cause a variation in behavior, which means that no reliable statements can be made. However, the ROM asymmetry can be determined with a margin due to the big difference of 40-50% between the knees in the initial phase.

### Practical use

No calibration method has yet been developed and validated. For the time being, a simple calibration strategy is being considered in which the knee sleeve is first calibrated on the healthy knee by performing a few full bends (0–130°) to determine the knee angles. Next, a few controlled squat movements are performed up to the maximum achievable knee flexion of the injured knee at that moment in order to align the two knee sleeve sensors. This allows an individual reference to be established, but this approach has not yet been tested for reproducibility and accuracy.

In addition to the measurement performance, additional practical limitations affect the current usability of the knee sleeve. The knee sleeve is not washable in its current prototype version because the electronic components cannot be removed by the user and the conductive yarns used are sensitive to water. Water contact affects the performance of the sensor. As a result, the knee sleeve cannot be used safely and hygienically in clinical practice or for long-term reuse at the moment.

### User Interface

In addition, in the current setup, only the knee angle is derived from the measured resistance value, based on a calibration table. Parameters such as consistency and asymmetry are defined but not yet calculated automatically at this stage. In addition, for user testing and validation, the operation of the system was simulated using a live graph generated with Python in a Streamlit environment. This environment served as a visualization of a possible app interface, but is not suitable for practical use. For actual application, further software development is necessary, whereby measurement data is automatically analyzed and translated into understandable values within an application.

## 15.4 Viability

The knee sensor sleeve has the potential to be economically and organizationally viable within the current healthcare context. Because the sensor is made of conductive yarns instead of complex and expensive sensor technology, the material costs can be kept relatively low (Appendix G). This keeps the total cost of the knee sleeve affordable, making it possible for patients to purchase the sleeve themselves without being a financial barrier.

The system in which the knee sleeve is owned by the patient offers advantages for both the patient and the physical therapist. For the physical therapy practice, this means that there are no additional organizational burdens, like managing inventory, maintenance and washing. This lowers the threshold for implementation in practice and increases the change of acceptance by healthcare providers.

Within the healthcare context, the knee sleeve can be a supportive tool in physical therapy treatment, particularly in the early stages of rehabilitation. The physical therapist keeps control of the treatment plan, while the knee sleeve gives additional insight into progress and therapy compliance, both inside and outside the practice.



Figure 116. Knee sleeves in use during running

## 16. Discussion and Conclusion

This chapter critically reflects on the concept through a discussion, outlines recommendations for future development, draws conclusions on the final design, and includes a personal reflection.

[16.1 Discussion](#)

[16.2 Recommendations](#)

[16.3 Conclusion](#)

[16.4 Alternative applications](#)

[16.5 Personal reflection](#)

### 16.1 Discussion

#### Desirability and user perspective

The results from the user tests and interviews show that the knee sleeve meets the needs and expectations of both patients and physical therapists. The positive attitude toward the concept shows that the product is perceived as desirable within the context of knee rehabilitation. In particular, the combination of measurement, feedback, and use outside of the practice aligns with the increasingly common way rehabilitation is organized.

At the same time, it appears that desirability depends heavily on context and user. While motivated and technically skilled patients clearly recognize the added value of data and feedback, not every patient wants or needs extensive insights or gamification elements to the same extent. This emphasizes the importance of personalization and optional features, so the system fits different types of users and rehabilitation phases.

For physical therapists, the desirability lies primarily in the supportive role of the knee sleeve. The product is seen as valuable as long as it gives insight without disrupting the workflow or creating additional burden. Research and interviews show that desirability can be reduced when data is too complex, too inaccurate, or too prominent during exercises. This emphasizes the importance of cautious and considered feedback, a principle that was incorporated into the interface design.

In addition, trust plays an important role in desirability of the system. Both patients and physical therapists must be able to trust that the measurements are consistent and reliable. Insufficient accuracy or wrong information and statements can negatively impact the perceived value.

In summary, the knee sensor sleeve is desirable as a tool that motivates, supports, and provides insight, as long as it is flexible in its application, meets varying user needs, and strengthens the physical therapist's role rather than taking it over.

#### Context dependence on sensor performance

While the results show that the concept is technically feasible, the evaluation also shows that the sensor's performance is dependent on the context in which it is applied. The difference between performance under laboratory conditions and during use on the knee shows the complexity of measuring on the human body. Factors like textile behavior, sensor length and anatomical variation play a role.

In addition, the size and shape of the knee appear to influence the measurement results. Anatomical differences determine how the sensor is stretched during movement. Because the strain sensor is sensitive to the way it is stretched, variations in knee size, contour, and movement can lead to differences in sensor measurements. This emphasizes the need for additional research into the relationship between anatomical variation and sensor output.

Besides these individual anatomical differences, repeated positioning of the knee sleeve also plays an important role. Because of the complex anatomy of the knee, it is difficult to position the knee sleeve in the exact same way every time, despite the positioning cues. Even small variations in sensor positioning and alignment can lead to noticeable differences in the measurement. This means that knee anatomy affects not only the absolute measurement but also the reproducibility of measurements over consecutive sessions.

To minimize this influence, it is important that the knee sleeve can be adjusted to the individual user. Offering multiple sizes can be a first step in achieving a consistent fit and sensor load, and further optimizing comfort. Furthermore, the patient owning the knee sleeve allows for careful adjustment and calibration to the user's specific anatomy, without completely changing these settings each time, as is the case with shared use by multiple patients. This can not only improve measurement consistency but also contribute to ease of use.

However, the variation in measurements with repeated placement indicates that recalibration with each new placement is likely necessary to link the resistance measurements with the correct knee angle. The current choice to calibrate the knee sleeve on the healthy knee using full knee flexions and to calibrate the knee sleeve on the injured knee using controlled squat movements is based on practical considerations but has not yet been investigated or validated.

### Measurement accuracy

The limited measurement accuracy and repeatability of the current prototype currently make the system less suitable for measuring exact flexion angles. At the same time, the results show that relative parameters, such as the number of flexions and the consistency of movement, can be reliably determined. These parameters are based on comparing consecutive movement patterns within a single session and are therefore less dependent on the absolute accuracy of the measured knee angle. Because consecutive flexions are measured consistently, changes in movement consistency and exercise patterns can be fairly accurately analyzed.

The validation test showed that the sensor's effective work range is currently limited to approximately 100° of knee flexion. According to the physical therapist involved, most exercises in the first phase of rehabilitation fall within this range, so this is not a major problem in the first phase. However, in later phases, when full knee flexion is the goal, it is important to be able to reliably measure angles up to 130°.

Due to the big difference in range of motion (ROM) between both knees in the early phase of rehabilitation, ROM asymmetry can, in principle, be detected at this stage, provided the knee ligaments are carefully and consistently calibrated. However, current measurement accuracy is still insufficient for measuring motion symmetry between both knees, because both sensors do not respond identically to the same movement due to small manufacturing variations.

### Prerequisites for implementation

Besides measurement accuracy and sensor performance, the knee sleeve's washability is an important limitation for practical application. In the current prototype, the electronic components cannot be removed by the user, and the conductive yarns used are sensitive to water, making regular washing impossible. This makes the system currently unsuitable for use in physical therapy practices, where hygiene is an important requirement for devices worn directly on the skin. However, an advantage of this design over systems based on IMUs is that all electronics are concentrated in a single location. This allows for relatively simple removal of the electronics by the user, making washing possible in the future.

While the knee sleeve has economic and organizational potential, successful implementation depends on how the product is positioned within the healthcare system. The low costs makes it attractive to offer the knee sleeve as a personal device, but this needs clear communication with patients about the system's purpose and limitations. The physical therapist also mentioned that proper instruction is important for reliable use. If users are not properly instructed on how to wear and apply the knee sleeve, inaccurate measurements can still occur despite an accurate sensor. Clear user instructions and guidance are therefore needed for successful practical application.

In addition, broader adoption will need attention to issues like data processing, privacy and integration with existing systems. These aspects were not addressed in this project, but they will play an important role in the product's market launch and scalability.

## 16.2 Recommendations

### Improving sensor performance

Although the current prototype is functional, its measurement accuracy remains limited, particularly when determining exact knee angles. Additional research and further optimization are needed to improve the integration of the strain sensor into the knee sleeve and thus increase the repeatability and accuracy of the measurements.

Additional research and improvements to the sensor's working range are needed to expand the measurement range to 130° to ensure applicability throughout the entire rehabilitation process. In addition, further research is needed into the influence of anatomical variation, knee size, fit, and positioning on the sensor output, to better understand and address variation between users and repeated placement.

Furthermore, research is needed into a validated and optimized calibration procedure that allows the knee sleeve to be reliably aligned, both individually, ensuring the correct resistance-to-knee-angle mapping, and between sleeves, ensuring they are aligned with each other. This is important for ensuring reliable measurements within and between exercise sessions. Finally, additional research is needed into measuring movement symmetry with industrially manufactured, identical sensors to further minimize sensor variation.

### Functionality and software

To make the system usable in practice, the software needs to be expanded to automatically calculate parameters like movement consistency, repetitions, and asymmetry. A user-friendly app environment must be developed that visualizes the data, as visualised in this project.

In addition, optimizing the electronics offers opportunities to reduce energy consumption. More efficient energy management can contribute to a longer service life, a smaller battery, and thus a more compact design. Further software and hardware optimization is needed for this.

Figure 117. Removable electronics example



## Hygiene and maintenance

For practical application in physical therapy practices and long-term use, research is needed to develop removable electronics and waterproof yarn to make the knee sleeve washable. This allows for safe and hygienic cleaning without affecting measurement performance.

## Product design and adoption

Offering multiple sizes is desirable because it can contribute to a comfortable fit and more accurate and reproducible sensor strain. In addition, making the patient the owner of the knee sleeve is recommended enabling precise adjustment and calibration initially with only small adjustments needed per session, and to increase engagement.

For broader adoption within healthcare, it is also necessary to address data handling, privacy, and security, as well as developing instructions and integrating with existing healthcare systems. Implementation within the rehabilitation process itself also needs additional attention to enable practical application.

## Clinical validation

Further research with larger and more diverse patient groups and within more physical therapy practises is necessary to further evaluate the reliability, usability, and clinical relevance of the knee sleeve. This should not only focus on technical performance but also on its impact on exercise consistency, adherence, and progress monitoring.

In addition, it is important to test the use of the knee sleeve in different rehabilitation phases and with varying knee and body types to improve generalizability of the results and support its applicability in clinical practice.

Furthermore, it is recommended to investigate the system's long-term stability during prolonged use within clinical settings. It is important to evaluate whether the measurements remain reliable and consistent over time to ensure the knee sleeve can support progress monitoring throughout the entire rehabilitation process.

## Optimalisation of knee sleeve

The physical design of the knee sleeve can also be further optimized. It is recommended that the conductive yarn between the electronics and the sensor is applied with the same density as the sensor. This reduces electrical resistance because the current follows a more direct path.

In addition, it is desirable to investigate a more qualitative solution for maximizing the sensor's stretch, which is achieved in the current prototype with a piece of non-slip elastic. It is also expected that the connections between the wiring and electronics are currently not robust enough for all possible conditions. Industrial connection methods should be used for more robust and reliable connections.

Finally, selecting a more breathable fabric can also contribute to further improving wearing comfort.

## 16.3 Conclusion

The goal of this graduation project was to develop a functional, comfortable and reliable textile knee sensor sleeve, consisting of an integrated strain sensor that continuously measures knee flexion during rehabilitation exercises. The desired outcome prioritized functionality, comfort, and reliability over maximum precision. It needed to be an accessible tool that supports and motivates patients, promotes adherence during rehabilitation, and enables patients and healthcare providers to collect objective data to be able to view and understand the rehabilitation progress. Based on testing, and evaluation phases, this goal has largely been achieved.

The developed prototype can measure knee flexion and translate movement data into insightful feedback. It is particularly suitable for monitoring relative parameters such as the number of flexions, movement consistency, patterns within exercise sessions, and range of movement symmetry. These features make the system useful in early-stage rehabilitation, where restoring movement control and building exercise consistency are central. Measuring precise knee angles across the full flexion range is not yet possible, because of limited accuracy and repeatability, with an limited effective work range of up to approximately 100 degrees.

User feedback indicates that both patients and physical therapist perceive the sleeve as a valuable tool for visualizing movement and progress, improving and understanding of rehabilitation status and supporting motivation. Besides its functional outcomes, the project shows that the sleeve is an accessible, cost-effective alternative to more complex measurement systems, which enables personal patient use and minimizes logistical burdens for physical therapy practices. By prioritizing wearing comfort, context of use, and integration into clinical workflows, the project goes beyond many existing prototypes, which often focus mainly on technical performance while neglecting these practical aspects.

In summary, this project shows that a textile knee sensor sleeve is technically feasible and desirable as a supportive rehabilitation tool when application and expectations are clearly defined. While it does not replace existing clinical measurement tools, it offers meaningful insight into movement, progress, and exercise behavior both within and outside practice. The project lays a solid foundation for further development and research into an accessible and functional rehabilitation tool.



Figure 118.

## 16.4 Alternative applications

Besides its current use in rehabilitation exercises, the knee sensor sleeve offers several interesting possibilities for the future. One option is wearing the sleeve all day to monitor daily knee use. However patients are not convinced yet, this can provide valuable insights into how often and intensively patients actually use their knee, something that, according to the orthopedist, is often under- or overestimated. Especially in the early stages of rehabilitation, when range of motion is still limited, the physical therapist mentioned that insight into daily activity can help to better understand the stress on the knee during daily activities.

Another interesting future development is combining the strain sensor with other sensors like IMUs. IMUs can accurately measure lateral movements and rotations, but are prone to drift and calibration errors. Strain sensors can easily record stretch and reliable relative movements during bending, but are less precise for exact angles. While combining these technologies may impact the accessibility and simplicity of the current prototype, their strengths complement each other and can create a more complete and reliable picture of knee movement.

Another potential application of the knee sleeve is to stimulate playful movement, for example, in children undergoing rehabilitation or requiring additional exercise. For example, a game like Flappy Bird could be linked to the knee sleeve, where bending the knee would make the bird to fly upward. This doesn't need precise angle measurement; it's mainly about stimulating movement and giving direct feedback on the movement itself.

In addition, the technology could be expanded to other joints, like the elbow. An elbow sleeve could, for example, provide support during rehabilitation after surgery or for conditions like tennis elbow.

These possibilities show that the knee sensor sleeve can go beyond knee rehabilitation. Further development and research are needed, but it shows the sleeve's potential for broader applications. Improving the accuracy and repeatability of the sleeve could also enable new applications where more precise angle measurements are valuable, for example, in sports.

## 16.5 Personal reflection

This project was full of surprises and learning experiences. I'm proud that I took on this challenge, despite my limited knowledge of electronics and my limited skills in coding, soldering, and sewing. By taking on this challenge, I got the most out of my final project and successfully achieved my learning goals.

The process, from optimizing a strain sensor, integrating it into a knee sleeve, and investigating the influence of the knee and movement on the sensor, to translating raw data into valuable insights for the user, made the project both technically challenging and motivating. The project offered a strong combination of technology and human interaction, a balance I value highly as a designer: a product that not only functions technically but also connects with the user and is aesthetically pleasing. Working on a product that can truly contribute to supporting people, rather than designing a standalone gadget, aligns with how I enjoy designing and what motivates me.

Because of my limited initial knowledge and skills, managing the project entirely on my own was exciting, but also challenging. I learned that asking for help from experienced people isn't a weakness, but rather important for preventing stagnation and keeping progress. As a designer, you're versatile and can handle many aspects of a project yourself, but you often lack the specific expertise to bring a concept to a truly valuable level on your own. Therefore, it's important to engage with people with the necessary knowledge and experience at the right time to ensure optimal development of the concept. Contact with experts within the various departments of the Applied Labs, as well as patients and healthcare providers, was very valuable and made a big difference to the project's progress and quality.

In addition, I have noticed that I am better able to reflect and critically examine my choices and priorities, which helped me to make well-considered design decisions. The project taught me to manage uncertainty and work iteratively; the process of trial and error, evaluating, and improving each time showed new insights that were important for further improving the concept (figure 119).

All in all, a very valuable project to conclude my studies with.

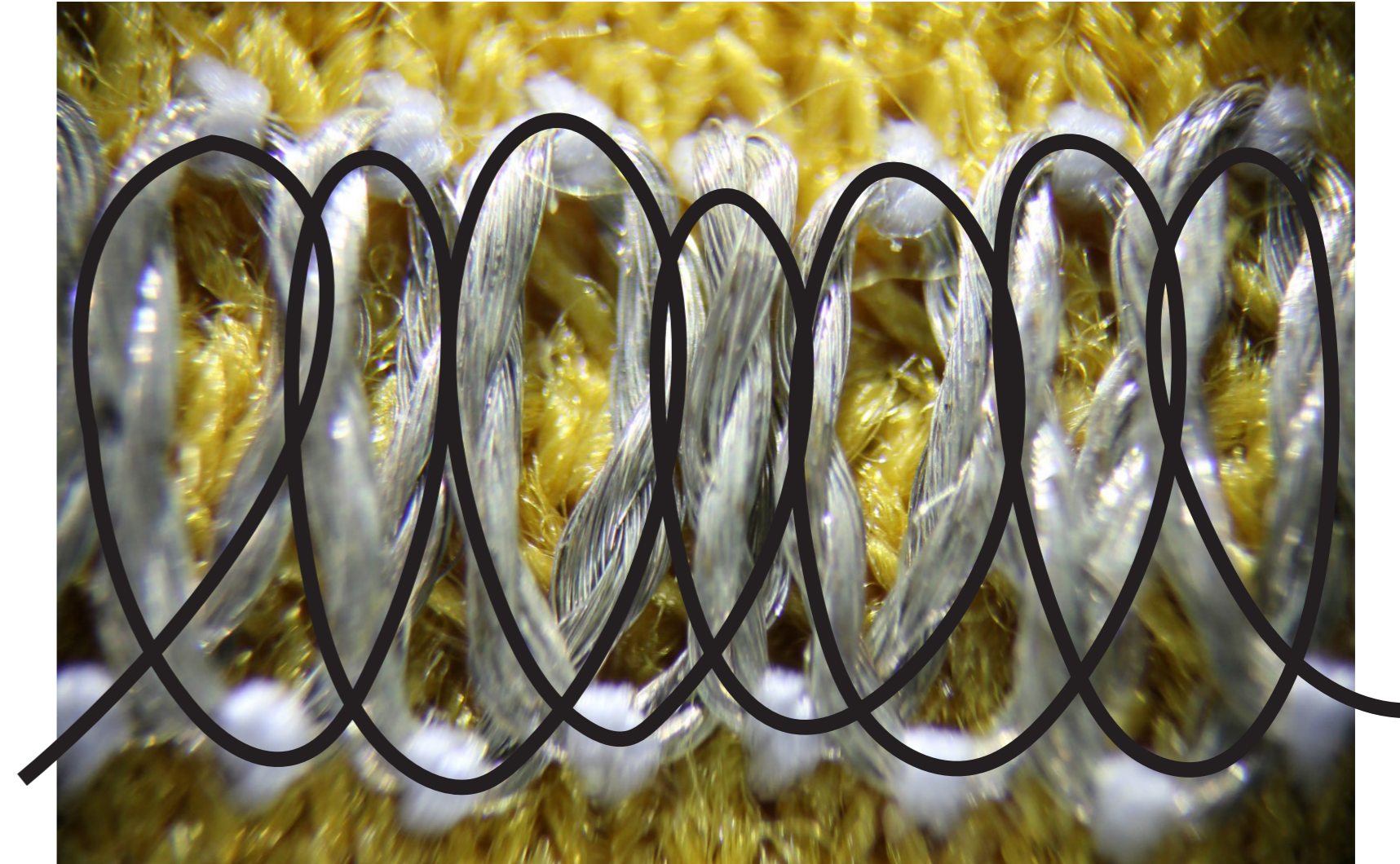


Figure 119. My project unfolded like the sensor operation in the knee sleeve; the Seeeduino marks the starting point of the project, with a clear goal in mind. Just like the current flowing through the sensor's loops, I went through multiple iterations: trial and error, adjustments, and improvements. In the end, the current returns to the Seeeduino to measure the voltage difference, just as I return to the starting point at the end to evaluate whether the goal of the project has been achieved.

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