Symphysis

Syncing Mind and Motion in Knee Recovery

A patient-focused wearable for an engaging and supported knee injury recovery

By Tim Robbert Bouwmeester to obtain the degree of master of science at the Delft university of technology to be defended publicly on the 19th of may 2025

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Thesis committee: Marijke Dekker, Mascha Slingerland

Glossery

During this study some complicated medical and technical terms are mentioned. In order to make this report more understandable a Glossery was created to make the report more readable.

Term	Definition
ACLR	*Anterior cruciate ligament reconstruction*
ACL	*Stands for Anterior Cruciate Ligament and is key ligament in the knee that helps stabilize the joint by preventing excessive forward movement of the tibia (shinbone) relative to the femur (thighbone)*
AI	*Artificial intelligents*
Anterior	*Front, the front side of the body*
Beachhead	*A beachhead market is a point where a product might enter the market to scale to the actual apli cation an example for this is entering the premium sport car market where cost are less optimized to scale to larger production for the average consumer*
BLE	*Bluetooth low energy*
BPM	*Beats per minute*
CPM	*Continuous passive motion: is a device that moves the knee a patient's knee.*
ECG	*Electrocardiogram: recording of the hearth pulse*
E-health	*Electronic health industry*
EMG	*Electromyography (electric signals from nerves system)*
Femorial condyles	*The femoral condyles are the two rounded promi nences at the lower end of the femur that form part of the knee joint. There are two condyles articulate with the tibia and the patella, allowing smooth movement of the knee*
Femur	*Bone connecting the hip and the knee*
Fibia	*Small bone running allong the Tibia*
Gait	*The pattern of how a person walks is called your gait*
GSR	*Galvanic Skin Response, a sweat response from the nervous system*
GUI	*Graphic user interface*
HRV	*Heart rate variability*
Illness beliefs	*A patient's perception and beliefs about their own ability and condition*
IMU	*Inertial measurement unit: Combination of sensors to measure inertia (acceleration, position, magnetic field)*
Jerk	*The change in acceleration over time*
KNGF	*Koningklijk nederlands genootschap voor fysiotherapie (Dutch national instutide for physiotherapy)*
Lateral	*Outside view, on the outside relative to the body, example lateral knee is the outside of the knee*
LCL	*Stands for Lateral Collateral Ligament and is Positioned on the outer side of the knee, the LCL connects the femur to the fibula.*
MCL	*Stands for Medial Collateral Ligament and Runs along the inner side of the knee, connecting the femur (thighbone) to the tibia.*
Medial	*Inside view, on the inside relative to the body, example medial knee is the inside of the knee.*
MVP	*Minimal viable product*
Myofascial	*The combination of connective tissue and muscles*
OA	*Osteoarthritis, A degenerative joint disease that occurs when the protective cartilage covering the ends of bones wears down over time, leading to pain, stiffness, swelling, and reduced mobility.*
Patella	*Kneecap*
Patellofemoral	*The joint connecting the knee cap and the*
PCL	*Stands for Posterior Cruciate Ligament and is Located behind the ACL, the PCL prevents excessive backward movement of the tibia and provides stability, especially during activities involving sudden deceleration or impact.*
Posterior	*Back, the back side of the body*
PPG	*Photoplethysmography: a simple optical technique used to detect volumetric changes in blood in peripheral circulation*
Quaternion	*A convenient mathematical notation for representing spatial orientations and rotations of elements in three-dimensional space. (w,x,y,z), (rotation, position)*
RMSSD	*Stands for Root Mean Square of Successive and calculates A time-domain measure of heart rate variability (HRV) that reflects para sympathetic ctivity.*
ROM	*Range of motion*
RR-intervals	*The time between two consecutive R-wave peaks of the heartrate, representing one full heartbeat. Measured in milliseconds (ms)*
Sagittal plane	*The side plane of the body*
SDNN	*Standard Deviation of NN Intervals, A time-domain HRV metric representing overall autonomic nervous system activity*
Tibia	*Bone connecting the knee and the ankle*
Tibiofemoral (TF) joint	*The joint connecting the tibia and the femur*
TKA	*Total knee Arthroplasty: the surgical treatment of replacing the whole knee with a prosthetic*
VR/AR	*Virtual reality/augmented reality*

Preface

This report shows the work of Tim Robbert Bouwmeester that completed the master graduation at the Faculty of Industrial Design Engineering of Delft University of Technology.

Acknowledgements

I would like to express my appreciation to everyone who contributed to this graduation project. Firstly, I would like to thank my chair, Marijke Dekker, my mentor, Mascha Slingerland, for their guidance and support throughout the project. Their feedback was essential to my progress and development. Furthermore, I would like to thank the experts, physiotherapists, rehabilitation specialists, and patients, whose insight helped identifying problems and forming my solution. Aditionally, I am grateful to the participants who took part in the user tests and provided their data for the validation of my concept.
Lastly, I would like to thank the support staff at the university for their assistance with academic writing, ethical procedures, and psychological support during this journey.

Abstract

This study was motivated by Exertise, a startup initiative I co-founded aimed at making home physiotherapy more engaging through gamified exercises and a Duolingo-like streak system. During this initiative, we encountered patients recovering from knee injuries who struggled with their rehabilitation process on a different level. This revealed an opportunity to design a patient-centred wearable to better support recovery in knee rehabilitation.

Knee injuries are increasing in the Netherlands, while many physiotherapists are leaving the profession due to high workloads and limited career growth, highlighting a growing gap in rehabilitation services. Through literature research and qualitative interviews, the rehabilitation process, patient challenges, biomechanics, and emotional adaptations after injury were explored. A stakeholder analysis and patient journey mapping revealed that a major barrier to recovery is the misalignment between physical and psychological rehabilitation, known as parallel recovery.

Further research into existing knee wearables and competitor analysis indicated a market gap. While current solutions focus on either physiological or biomechanical measures, few integrate both to address parallel recovery. With the rise of E-health technologies and constrained healthcare access, moving the patient more to home and self management, a system promoting synchronized physical and mental rehabilitation is viable.

Based on these insights, the project scope shifted towards developing a system that enhances parallel recovery using actionable sensor data. Three design directions were developed, with the final concept being Symphysis. Symphysis is a product-service system that detects physiological responses in relation to knee movement through a sensor kit combined with a mobile app and therapist dashboard. It enables patients and physiotherapists to identify emotional challenges during rehabilitation through a unique feedback loop.

The system uses three wearable modules placed on the thigh, shin and wrist, integrating heart rate (PPG), galvanic skin response (GSR), and inertial measurement unit (IMU) sensors. By analysing changes in heart rate variability, skin conductance, range of motion, and movement biomechanics, Symphysis provides insights into how psychological states influence movement patterns. The wearable connects via Bluetooth Low Energy (BLE) to an app that visualizes the data for both patients and therapists, supporting live session tracking and telerehabilitation.

To test the concept, a functional prototype was developed and evaluated with nine healthy participants. Participants completed three conditions: resting baseline, squats without cognitive load, and squats with a cognitive load (counting backwards in 7s).

Paired sample T-tests showed a significant increase in GSR ($P = 0.038$, $d = 0.83$), internal/external rotation range of motion ($P = 0.045$, $d = 0.28$), and velocity ($P = 0.049$, $d = 0.17$) under cognitive load. Participants also took significantly longer to complete exercises under cognitive load ($P = 0.021$, $d = 0.96$), indicating clear effect of the cognitive load, but the differences in time allowed participant use different adaptation strategies, which made comparison more difficult.

These results suggest that Symphysis can detect emotional influences on movement. However, sensor reliability, particularly in the wrist module, needs improvement. Future work should refine the hardware, set a fixed exercise pace to minimize adaptation strategies, and conduct further validation before drawing conclusions and beginning clinical trials.

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Introduction

Before starting this graduation project, the subject was identified. In this section the context of the this study is explained as well as the problem definition that started this project.

Problem context

75% of physiotherapy patients do not do their home exercises properly (FysioFacts: Cijfers Over Fysiotherapie KNGF, 2023) Therefore, I co-founded Exertise, a startup initiative to make home physiotherapy more fun and engaging. Currently we are developing a solution with an IMU (inertial measurement unit) sensor in combination with an app to make the home physiotherapy more engaging with the use of gamification and active feedback.
At Exertise our main stakeholder is the patient. Other stakeholders of Exertise are: medical experts like physiotherapists, surgeons and also insurance companies and businesses.
During our efforts, we encountered many patients with knee injuries or a history of knee injuries. A common theme among them was the struggle with fear of moving as freely as they did before the injury, along with a persistent sense of instability, even after completing rehabilitation. We found it challenging to apply our current solution effectively to this issue, which presents a valuable opportunity for me to explore a more tailored approach to address this specific problem.

Problem definition

Knee injuries are highly prevalent in the Netherlands, especially in sports. A 2022 survey by RIVM and CBS identified that 11% of respondents reported sports-related injuries, with knee injuries accounting for 26% of these cases (Does et al., 2023). Of the estimated 5.1 million people who experienced sports-related injuries, 2.1 million required physiotherapy, and approximately 53200 cases were classified as severe, necessitating hospital treatment. Football is noted as the primary setting for such injuries (Does et al., 2023).
In addition to sports injuries, knee osteoarthritis affects approximately 1.6 million people in the Netherlands (Artrose Volksgezondheid en Zorg, 2022), often resulting in chronic pain and limited mobility. For both injury and osteoarthritis patients, knee issues lead to challenges with stability, pain, and reduced quality of life.
Rehabilitation is not only physically demanding but also associated with psychological hurdles, such as fear of reinjury, mental health challenges, and diminished motivation. Evidence indicates that motivation, mindfulness-based practices, and goal-setting strategies significantly impact rehabilitation outcomes (Abdulhussein, 2024).
All these facts show that innovation in knee rehabilitation is an viable problem space with potential for unique oppurtunities.

Despite the critical role of physiotherapists in guiding patients through effective rehabilitation, there is a shortage of practitioners in the Netherlands. Many physiotherapists are leaving the field due to low wages and better career opportunities elsewhere. According to Lodi Hennek, chair of the KNGF, a third of physiotherapists may leave the profession within the next five years if conditions do not improve (NOS, 2024). The physiotherapy field is striving to innovate despite limited financial resources, with an increasing focus on integrating technology, such as VR, AI, and mobile applications, to support patient care (FysioSupplies, 2024).
The Dutch government is investing in E-health solutions. The goal is to have 50% more healthcare in home environment by 2030 (3.2 Organiseerbaarheid En Betaalbaarheid Van De Zorg, Ministerie Van Financiën - Rijksoverheid, 2023).
A patient-centred wearable device that supports knee rehabilitation by tracking progress, enhancing patient engagement, and providing post-recovery support could address both patient and physiotherapist needs. Such a solution would promote patient confidence and enjoyment during rehabilitation, while also offering long-term stability and reassurance in knee performance after formal rehabilitation ends. Consequently, the following design assignment is proposed:

Design a patient-centred wearable that enables knee rehabilitation progress tracking, improves engagement, and enhances post-recovery support.

1. Research

This chapter examines the stakeholders, their roles, and the challenges they face in the patient journey. The analysis is based on a review of the literature on anatomy and knee rehabilitation processes, as well as qualitative interviews conducted with stakeholders, patients, and experts. To ensure ethical data collection, a consent form was developed for these interviews (see Appendix A).
In addition, the use of technology in knee wearables was explored to assess its potential for addressing challenges in the patient journey and to evaluate its feasibility. Market trends and competitors were also analysed to identify opportunities and overlooked details. This analysis helps ensure the development of a viable solution with a distinct unique selling point.
Finally, the scope of the project was defined to establish the design space for potential solutions along with the design criteria.

1.1. Anatomy & Biomechanics

To understand the rehabilitation processes of knee injuries. A basic understanding of anatomy, biomechanics and how the body functions is needed in order to make a fitting solution. Furthermore, addressing these topics in the beginning of the study makes conversations with experts more meaningful and makes explaining possible solutions easier.
The knee plays a vital role in the kinematic chain, working in harmony with the hips and feet to facilitate complex movements. This section focusses on the anatomy of the knee and its supporting elements like muscles and tendons. In addition to that an introduction to the nervous system and psychological responses is given to understand implementation of these aspects in product development.
Lastly the anthropometrics of the knee are explained. Understanding the differences in knee sizes assists in making a wearable solution that fits.

Knee anatomy

The knee joint is one of the strongest and most complex joints in the body, connecting the upper and lower leg to facilitate lower limb movement. It provides stability and acts as a shock absorber during daily activities.
The knee comprises two synovial joints: the tibiofemoral (TF) joint and the patellofemoral (PF) joint. Synovial joints allow smooth motion between bones, aided by synovial fluid, a lubricant that reduces friction. They are encased in a joint capsule and lined with cartilage, which cushions the bones and ensures seamless movement ("Cartilage Tissue and Knee Joint Biomechanics", 2023). The knee joint consists of four primary components, see figure 1:

- **Bones:** The femur, tibia, and patella articulate the upper and lower leg.
- **Ligaments:** Stabilizers like the (ACL, PCL, LCL and MCL) maintain structural integrity.
- **Cartilage:** The menisci distribute loads and absorb shocks.
- **Muscles and tendons:** The quadriceps and hamstrings generate movement through flexion and extension.

Vascular and nervous structures also play a vital role. Major blood vessels, such as the femoral and popliteal arteries, supply the muscles, while the sciatic nerve and its branches provide motor and sensory functions. These nerves transfer electromagnetic signals from and to the brain to create cognitive and psychological input and output. How this works in detail will be described on page 12.
Understanding these elements are essential for measurements in solution development later in this study. For further anatomical details, see Appendix B

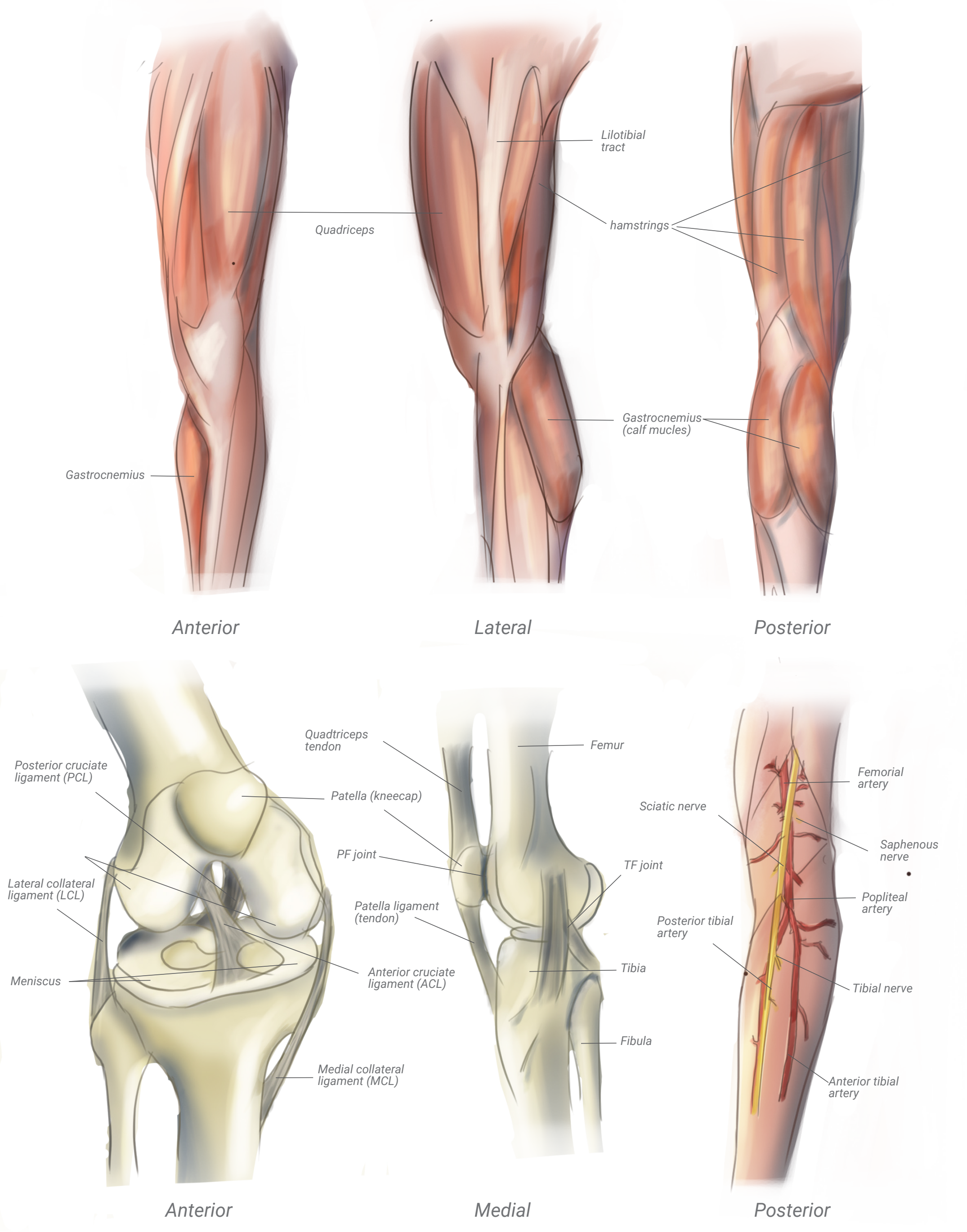


Figure 1: Anatomy of the knee

Biomechanics of the knee

Biomechanics tries to describe the movement in organisms to mathematical models in order to understand or predict what is going to happen, encompassing parameters such's as range of motion (ROM), speed, acceleration and forces on joints. Understanding the mathematical parameters to describe knee movement is essential for design a technical wearable solution.

The knee is primary a hinge joint that facilitates flexion and extension but also has slight rotational and translational movements that enhance efficient movement. These slight movements besides flexion and extension allow for stabilization during full extension, especially in weight bearing positions, see figure 2

The screw-home mechanism

The screw-home mechanism is a unique kinematic feature of the knee that contributes to joint stability in full extension, see figure 2. This mechanism minimizes effort when standing and contributes to efficient motion. It involves external rotation of the tibia (or internal rotation of the femur in a closed-chain movement) during the final degrees of knee extension (Kapandji, 1987). This motion occurs due to the asymmetry of the femoral condyles, with the medial condyle being longer and more curved than the lateral condyle (Herzog & Read, 1993).

- Open-chain movement, see figure 3: During non-weight-bearing extension, the tibia externally rotates relative to the femur (Kapandji, 1987).
- Closed-chain movement. see figure 3: In weight-bearing scenarios, the femur internally rotates on a fixed tibia (Nordin & Frankel, 2001).

The anterior cruciate ligament (ACL) plays a role in guiding tibial rotation and preventing excessive anterior translation of the tibia. Additionally, the vastus medialis oblique (VMO) muscle, one of the quadriceps muscles, assists in stabilizing the patella and contributes to the rotational alignment of the knee joint (Herzog & Read, 1993). Electromyographic (EMG) studies have shown reduced quadriceps and hamstring activity when the knee is fully extended, supports postural efficiency and reducing fatigue during prolonged standing (Kettelkamp & Jacobs, 1972).

Knee joint range of motion and kinematics

A healthy knee exhibits specific ranges of motion, these can vary a bit due to genetics, lifestyle and fitness level. The ROM values for the" healthy" knee joint are as described in table 1. These kinematic values are essential when assessing knee rehabilitation, as deviations from normative ROM values can indicate joint dysfunction or compensatory movement patterns. The axis of the knee are visualized in figure 4.

Movement	*Degrees of motion*	*Primary muscles*	*Femur relative to Tibia*
Flexion	*0-130° (160° passively)*	*Hamstrings, gastrocnemius*	*Rolls backward and slides forward*
Extension	*0 -5° (-10° hyper)*	*Quadriceps*	*Rolls forward and slides backward*
Internal rotation	*10-15° (flexed)*	*Semitendinosus, semimembranosus, gracilis, sartorius*	*Rotates internally on tibia*
External rotation	*10-15° (flexed)*	*Biceps femoris*	*Rotates externally on tibia*
Varus (adduction)	*2-3°*	*Medial collateral ligament (passive restraint)*	*Slight lateral tilt*
Valgus (abduction)	*2-3°*	*Lateral collateral ligament (passive restraint)*	*Slight medial tilt*

Table 1: knee movement summary (“Cartilage Tissue and Knee Joint Biomechanics”, 2023)

Velocity, acceleration and jerk in knee biomechanics

In addition to position tracking, analysing velocity and acceleration provides valuable insight into knee joint performance. Angular velocity (rate of change of angular position) and angular acceleration (rate of change of angular velocity) are valuable metrics in understanding knee movement efficiency. Increased variability in these parameters may indicate neuromuscular instability or strange movement patterns (Winter, 2009).
A higher level of jerk (the rate of change of acceleration) is often associated with movement inconsistency and abrupt changes in motion. Elevated jerk values can indicate difficulty in smoothly controlling movement, which may be linked to issues in motor control or psychological stress responses. Fluctuations in jerk may serve as an indicator of increased cognitive or emotional stress affecting movement patterns (Friedman, 2007). patients experiencing stress related movement irregularities may exhibit heightened muscle contraction, leading to inefficient motion and increased joint strain.

Concluding, the biomechanics of the knee mostly revolved around maintaining proper range of motion, mainly because of maintaining efficient movement considering the screw-home mechanism. Velocity and acceleration can be used to judge consistency in movement while Jerk can be used to determine “smoothness” of movement which can be used as indicator of poor motor control or psychological stress responses.

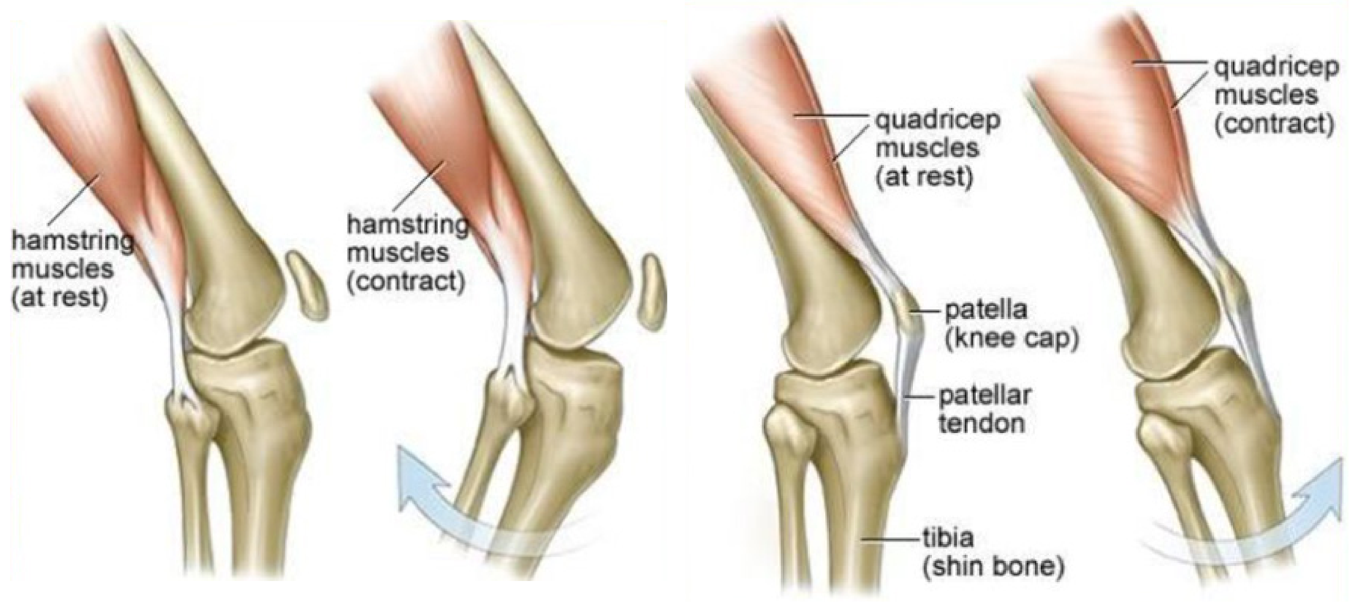


Figure 2: Screw-home mechanism

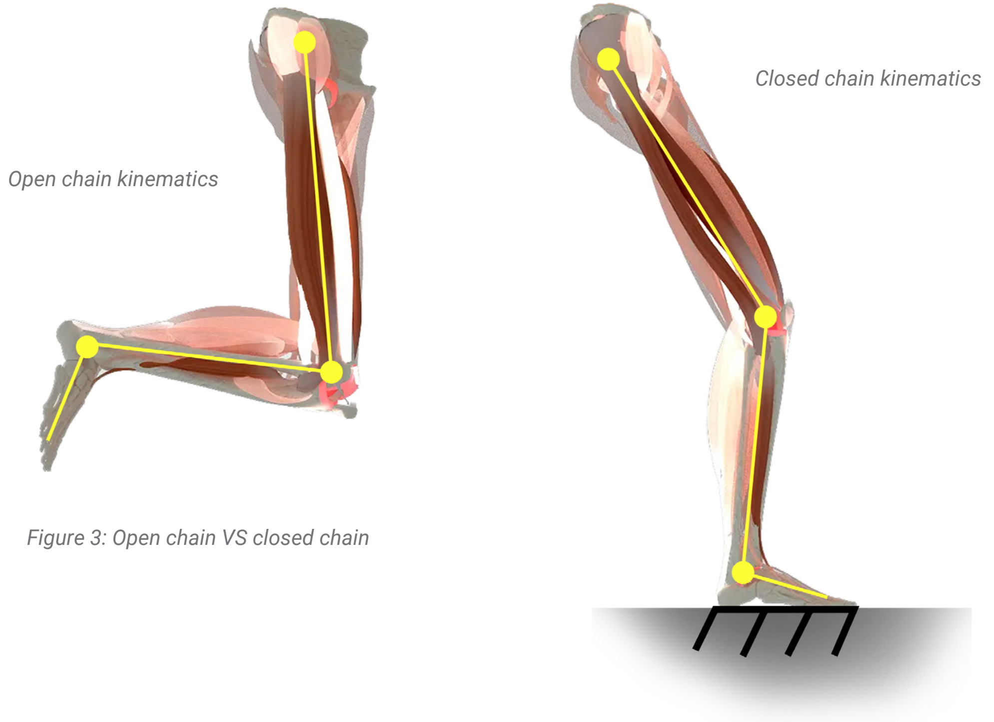


Figure 3: Open chain VS closed chain

Figure 4: Axis and Ground reaction forces

The nervous system in knee rehabilitation

The nervous system is an electromagnetic network that control body functions, perception and movement. The nervous system has two major components: The central nervous system (CNS), the brain and the spinal cord and the peripheral nervous system (PNS), consisting of sensory and motor nerves that connect to the CNS and the rest of the body. The nervous plays a functional role in the motor control (proprioception), pain perception, emotion regulation and recovery. These aspects are crucial in knee rehabilitation.

The PNS communicates real time sensory input to the CNS helping to maintain balance, coordination and movement efficiency. During injury the nervous system often modifies movement patterns, often leading to compensatory behaviours. These adaptations can hinder recovery by contributing to instability or causing chronic pain. (Lephart et al., 1997)

This nervous system can be controlled actively by the brain but also has the autonomic nervous system (ANS). This part of the nervous system consists of the sympathetic and parasympathetic branches.
The Sympathetic nervous system (SNS) becomes active in the "fight or flight response", triggering physiological changes including increased heartrate, heightened alertness and dilated pupils. One of the responses to the SNS activation is the change in electrodermal activity (EDA). This is also known as the galvanic skin response GSR (Critchley, 2002).
The GSR refers to the variations in skin electrical conductance, which are influenced by sweat gland activity. These sweat glands located in high density areas such as the foot soles, hand palms, fingertips and wrist are directly controlled by the SNS. When the SNS is activated due to emotional stress, pain or exertion these sweat glands become more active increasing skin conductance (Critchley, 2002). Therefore, the GSR is a good way to measure atomic nervous system activity.
Pain is a complex sensory experience, pain signals travel from the knee to through sciatic nerve to the CNS (spine). These signals are processed in the thalamus, somatosensory cortex, and limbic system. The limbic system, especially the amygdala and the prefrontal cortex influence pain perception and emotion regulation. Therefore, pain can also be influenced by emotion and psychological factors such as fear and stress. Heightened SNS activity can amplify pain perception. Therefore, good emotional regulation can reduce pain perception enhancing rehabilitation outcomes and perception (Apkarian et al., 2011).
The SNS can impact rehabilitation effectiveness for example a patient with fear of movement (Kinesiophobia) sometimes cognitively expect a pain response activating the SNS. The patient unconsciously actives muscles resulting in stiffness and reduced fine motor functions negatively influencing performance.
The parasympathetic nervous system (PNS) facilitates the "rest and digest" state of the body. In knee rehabilitation this state is crucial for promoting recovery, tissue healing and recuing inflammation.

One of the key indicators of the activation of PNS and SNS is heartrate (HR) related measures. Heartrate is often measured in beats per minute. The time between these heartbeats can differ and is known as heart rate variability (HRV) and is often measures in milliseconds. HRV is a good indicator of ANS function and emotional resilience. A high HRV indicates strong parasympathetic activity, flexible in adapting to stress and efficient recovery mechanisms. A low HRV indicates domination of the sympathetic response resulting in reduced adaptability to emotion and potential stress of body fatigue. (Harvard Health Publishing, 2023) (Zhaoxin Zhu., et all., 2023)
HRV is a valuable metric in rehabilitation, as it reflects an individual's physiological response to pain, stress, and movement demands. A higher HRV is generally associated with better recovery, emotional regulation, and resilience, whereas a lower HRV can indicate prolonged stress or impaired recovery mechanisms. (Harvard Health Publishing, 2023)

Balancing the PNS and SNS activity of the atomic nervous system is crucial for knee rehabilitation. Increasing PNS activity by techniques like breathing and mindful movement can reduce pain perception, improve proprioception and recovery for optimal rehabilitation outcomes and experience.

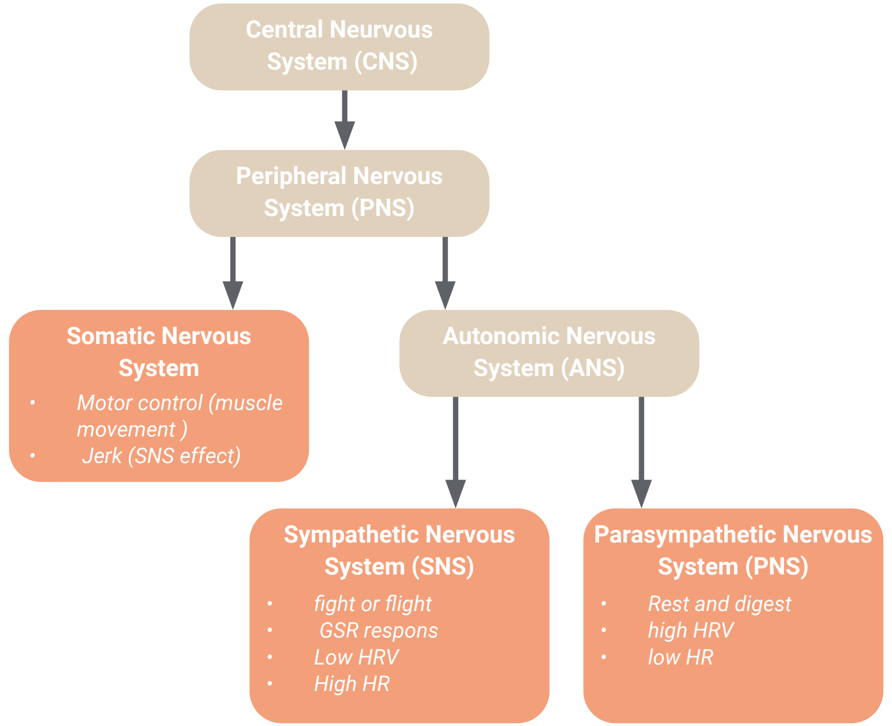


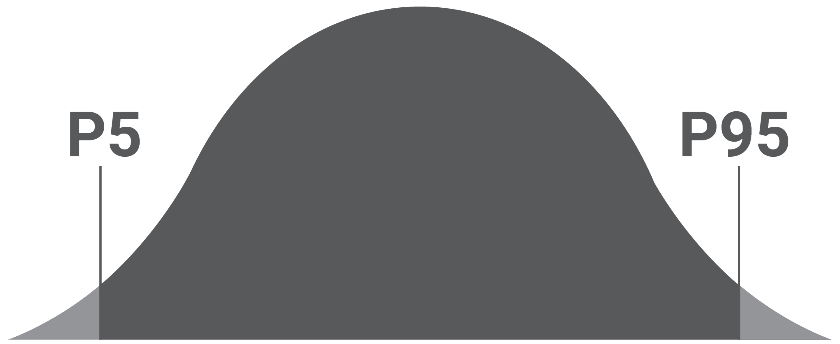
Figure 5: Schematic Nervous system display

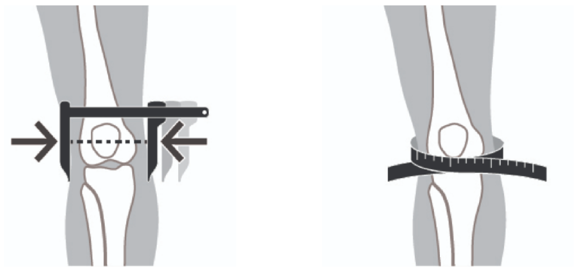
Anthropometric knee data

To create an ergonomically correct knee wearable, it's important to understand the variation in knee-related anthropometric measurements across populations. These measurements help ensure the device can be adjusted to fit a wide range of users effectively, see table 2.
These dimensions accommodate about 90% of the global population, with the 5th percentile representing smaller individuals (typically females) and the 95th percentile covering larger individuals (typically males). Variations by region, ethnicity, and age group are also relevant. Aitken, S. A. (2021).
Important to consider is that during intense rehabilitation programs the knee has stages of swelling, inflammation and effusion. Therefore, the knee can be thicker and thinner during the process, therefore adjustability of the wearable is needed.

Measurement	Mean ± SD (mm)	Range (mm)	5th Percentile	95th Percentile	Sources
Femur Length	500 ± 48	393–584	422	568	Aitken (2021)
Tibia Length	390 ± 38	308–465	334	452	Aitken (2021)
Tibial Plateau Width	71 ± 7	56–89	60	85	Mahfouz et al. (2012)
Knee Circumference	352 ± 28	287–421	305	401	Aitken (2021)
Mediolateral Width of Femur	84 ± 6	71–96	75	94	Mahfouz et al. (2012)
Patellar Width	48 ± 5	39–59	41	57	Mahfouz et al. (2012)
Thigh circumference	550 ± 50	450–650	470	630	Fryar et al. (2012)
Calf (Shin) Circumference	360 ± 30	300–420	310	410	Fryar et al. (2012)

Table 2: Anthropometric data knee wearable related measures





1.2. Qualitative interviews

Now the anatomy and biomechanics are clear, understanding of knee rehabilitation processes is needed. Therefore, qualitative interviews were conducted with patients, medical professionals and experts. This section describes the goals of the specific interviews and what was found in the interviews.
During these 30-45 min conversations an audio recorder was used if the participants agreed to with an inform consent, see appendix A. If the participant did not agree to audio recording notes were taken. The audio files were transcribed and translated when needed
The results of the interviews are used as a source to construct a stakeholder analysis, patient journey and product requirements. Furthermore, some experts were consulted in order to find good way to test the solution proposal.

Patients

Introduction

Patients are central to knee rehabilitation. Their experiences, challenges, and progress determine the effectiveness of rehabilitation wearable support systems. Understanding their struggles, motivations, and decision making processes helps in designing solutions that assist in meaningfull changes in their rehabilitation journey.

Method

Interviews are conducted with ten patients, each suffering from different knee injuries:

- Three patients with ACL injuries.
- Two with MCL tear injuries.
- One with osteoarthritis requiring a total knee arthroplasty (TKA).
- One with multiple ligament tears.
- One with meniscus issues.
- One with jumper's knee (knee tendonitis).
- One with recurring patella dislocation.

Patients are encouraged to share their personal rehabilitation journeys, the physical and mental challenges they encountered, and their views on rehabilitation support systems. The participants in these interviews will stay anonymous because of personal information being shared. The interview will be a conversation guided by topics to discuss:

1. Personal Experience with knee rehabilitation
2. Challenges and difficulties encountered
3. Perception of effective rehabilitation (perfect scenario)
4. Tools participants used themself (use of brace or other tools)
5. Technology and monitoring (wearable solution discussion, measurements desired features)

Results

The interviews resulted in a few themes patients encounter during rehabilitation:

Mental Challenges of Adapting Post-Injury

Many patients experience significant mental challenges while adapting to life after an injury. The sudden need to modify daily routines and physical activities can be mentally exhausting. The inability to participate in previously enjoyed activities often leads to feelings of frustration, restriction, and helplessness. Several patients described a sense of loss, not only in terms of physical capability but also in their identity, particularly for those deeply engaged in sports or physically demanding professions. Adapting to new limitations required substantial psychological effort, with some patients struggling with anxiety and even depressive symptoms.

Medical Decision-Making Stress

A common challenge reported by patients was the overwhelming nature of medical decision making. Facing complex choices regarding treatment options often led to decision making fatigue. Patients described feeling pressured to make significant decisions about surgical procedures and rehabilitation approaches within tight time constraints. One patient with an ACL tear explained the stress of choosing between a donor ligament transplant, hamstring reconstruction, or non-surgical rehabilitation, each with varying implications for mobility and long term recovery. The complexity of these decisions, coupled with the potential for irreversible outcomes, caused considerable mental strain. Several individuals also expressed concerns about the reliability of medical advice and the difficulty of processing conflicting opinions from different specialists.

Trust in Healthcare Professionals

Trust in healthcare professionals emerged as a crucial factor influencing rehabilitation experiences. Patients emphasized that establishing trust with their physiotherapist and medical team facilitated open communication and a more effective recovery process. A trusting relationship allowed them to express concerns honestly and receive tailored guidance. Conversely, a lack of trust led to hesitation in sharing struggles, with some patients fearing that raising concerns about ongoing pain or difficulties might be interpreted as an indictment of their surgeon's skill. This hesitancy sometimes resulted in unaddressed issues, which negatively impacted their rehabilitation progress. A few patients even switched healthcare providers mid-treatment due to feeling unheard or dismissed, further complicating their recovery journey.

Fluctuating Motivation

Motivation levels fluctuated throughout the rehabilitation process. Initially, patients found it easy to stay motivated due to rapid improvements, such as regaining movement and achieving early functional milestones. However, as rehabilitation progressed and visible improvements became less pronounced, many individuals experienced a decline in motivation. One patient reflected:
"At first, everything feels like a victory. Every week you see changes. You can move again, then you can walk. But then, suddenly, progress slows, and it feels like you're stuck."
This plateau phase was particularly challenging for patients who had high expectations for their recovery timelines. Many described feelings of stagnation, frustration, and uncertainty about whether they were doing enough to improve. For these patients, this period was especially difficult, as they often compared their recovery to teammates or peers who appeared to be progressing faster.

The Role of Social Support

The presence of strong support networks played a significant role in rehabilitation. Patients who received encouragement from family, friends, and teammates reported feeling more motivated and emotionally resilient. Training in groups with individuals who had experienced similar injuries was particularly beneficial for some, as it provided a sense of community, relatability and understanding. One patient shared:
"Having a teammate help me going through rehab with me made all the difference. We pushed each other to keep going, and it helped me stay focused."
However, social support was a double-edged sword for some. While it provided motivation, it also created unintended pressure. Patients who saw others recovering faster sometimes felt discouraged or questioned whether they were doing enough. One individual noted:
"It was tough seeing someone who had the same injury as me progressing faster. It made me doubt my own recovery process."
This comparison sometimes led to unnecessary self-imposed stress, further impacting mental well-being.

Confidence and Fear of Reinjury

Confidence in physical abilities fluctuated throughout rehabilitation, particularly in the later stages. Many patients reported a lingering fear of reinjury, which made them hesitant to push themselves in movement and exercise. For example, one patient admitted:
"For a long time, I was afraid to jump. I knew I was supposed to be ready, but my mind wouldn't let me take that step." Another patient stated "depending on the weather I am afraid to walk outside because I am afraid to fall. I know I can now, but I still do not do it"
At the same time, some patients experienced overconfidence, which occasionally resulted in setbacks. Encouraged by initial progress, they sometimes pushed beyond their limits too soon. One individual described how returning to group training too soon led to a significant setback:
"I was feeling great and thought I was ready for a full training. The energy from my teammates lifted me, but I overestimated my knee's strength. The next day, I realized I had overloaded it, which slowed my recovery and was a big mental hit."
Balancing confidence with caution was a common struggle, highlighting the psychological complexity of physical recovery. Many patients emphasized the importance of gradual exposure to higher intensity activities to rebuild confidence without risking reinjury.

Use of Tools and Supports

Patients used a variety of tool during rehabilitation, ranging from products to accommodations. Some patients used the gym as a tool to manage their own adherence to exercises and taking care of scar tissue. Other patients used more tools as crutches and braces.
Many patients used a brace as a mental supportive tool for intense physical activity, one patient explained:
"I have a brace for when I need to do more demanding physical activity, this brace was a bit expensive and is made for ACL support. I do not need it often, but is gives me more security".
Some patients also stated that some rehabilitation clinics also came with nutrition and psychological support that they used. One patient still trained at the rehabilitation clinic even when the rehabilitation is complete.
"I pay some extra each month but I can train there and if I have any questions or doubts, I can quickly ask my physiotherapist".

Wearables and Monitoring Progress

When discussing a wearable solution to support knee rehabilitation, patients found that having access to measurements throughout the rehabilitation process helped them better understand their injury. One patient shared:
"My injured leg was so much smaller than my non-injured leg, so I assumed it was weaker. However, when I did a comparison test on the leg press with my physiotherapist, I was surprised to learn that my smaller injured leg was actually stronger than my healthy leg. After that, exercising became easier."
Patients also mentioned that knowing someone was monitoring their progress would make them feel taken seriously. Being able to track incidents, such as a misstep, a fall, or a movement that caused pain and discuss them later with their physiotherapist was seen as beneficial. Regarding the wearable itself, patients emphasized that it should be quick to set up, comfortable, and easy to use.

Views on Gamification and Self-Reflection

Opinions on gamification were mixed. Some patients didn't care much about it but acknowledged that monitoring home exercises would improve adherence. One patient admitted,
"I would feel a bit awkward if I came to my physiotherapist and he already knew I hadn't done my exercises. I think that would push me more."
Others felt that gamification could make exercises more engaging, with one patient saying,
"If the exercises were fun enough that I actually looked forward to them, that would be great."
Patients also expressed interest in tools for self-reflection within the app, such as questionnaires. As one patient put it:
"The physiotherapist doesn't feel what you feel." Another shared, "I didn't realize I was mentally blocking myself until after I overcame it."
At the same time, some patients were concerned about being overwhelmed with too much information from the wearable. They stressed the importance of receiving data that is not only relevant but also actionable. As one patient put it:
"When I get information from a wearable, I want to be able to do something with it."

Discussion

The findings highlight the complex interplay between physical and psychological challenges in knee rehabilitation. Ensuring that patients feel heard, supported, and guided in their decision-making can improve adherence to rehabilitation programs.
A key finding is the psychological strain patients experience during rehabilitation, many struggle with mental and emotional struggles especially when adapting to new physical limitations. Decision making fatigue was another common issue, as patients struggled with complex treatment choices, often under time constraints. Trust in healthcare professionals played a critical role, with those who felt heard reporting better rehabilitation experiences, while others who felt dismissed sometimes changed providers, complicating their recovery.
Motivation and adherence fluctuated throughout rehabilitation. While early progress kept patients engaged, many found the plateau phase frustrating, especially after regaining basic function and when comparing their recovery to others. Social support could be seen as a double edged sword, it boosted motivation for some but created pressure for others. Confidence in physical abilities also varied, with some patients fearing reinjury and avoiding certain movements, while others pushed too hard, leading to setbacks. This highlights the importance of gradual progression with proper guidance.
Patients used various rehabilitation tools, such as gym access, braces, and continued physiotherapy support. Wearable technology was seen as promising for tracking progress and improving self awareness, but concerns about information overload emphasized the need for clear, actionable data. Gamification had mixed responses, some saw it as unnecessary, while others believed it could boost adherence and engagement. Additionally, self reflection tools like questionnaires were valued for capturing patient experiences that might otherwise go unnoticed by physiotherapists.

The limitations in this study are the focus on qualitative interviews mean a small and diverse number of participants. Most of the participants had acute knee injuries like ligament tears. Participants with overuse injuries like osteoarthritis where minimal this can give a bias in insights towards participants with acute injuries. Furthermore, all participants were interviewed in the Netherlands which might be give results a demographic bias.
Additionally, the data was captured in a single point in time and did not capture patient perspectives over time. Also, patient did agree to share their story, but they could hold personal information to themselves or adjust their story to make it less personal.

Conclusion

The qualitative interviews with patients underline the need for a supportive product that go beyond physical recovery and also consider the psychological aspects of rehabilitation These findings show that a well-designed wearable rehabilitation system should provide actionable feedback, reflection opportunities on certain activities and events and most importantly facilitate communication with healthcare providers while avoiding unnecessary overloading.
For the wearable solution to be effective, it should be quick to set up or put on, comfortable and easy to use. Monitoring missteps, falls or pain inducing moments and daily activities could enhance patients' confidence and communication with the medical professionals. Furthermore, it could save patients time by reducing physical sessions in the later stages by enabling telerehabilitation options.
While gamification may not appeal to all patients, personal approach to engagement, such as rewarding adherence and making home exercising more fun and feel less like a chore could improve motivation.
During the design process of the wearable system usability and actionable data are important aspects for patients. Avoiding cognitive loading while maximizing usefulness should be considered in the information delivery of the wearable. lastly keeping a personalized approach and holistic view on their rehabilitation by addressing both physical and psychological aspects in knee rehabilitation technologies can better support patients in achieving long term success.
This study considers the perspectives of patients on their rehabilitation at the time. In order to make a complete picture the medical professionals' perspectives are also important. Because of the small sample size and interviews being conducted only in the Netherlands, it is important to combine these insights with the literature to see similarities over healthcare systems and larger participants studies to completely understand the patient journey and the stakeholders involved.

Medical professionals

Introduction

Understanding patient needs in rehabilitation is important for designing a wearable design. Medical professionals like physiotherapists and surgeons play a crucial role in guiding the rehabilitation process. Understanding their challenges in treatment, making rehabilitation plans and how they would integrate new technology into their practice can improve the effectiveness of the wearable design.

Method

In this study six medical professionals were interviewed including primary care physiotherapists (3), a rehabilitation Docter/physiotherapist (1), an orthopedic surgeon (1) and a former physiotherapist (1). Topics that guided the interviews where:

1. Rehabilitation guidelines
2. Common patient challenges and how they help patients overcome these
3. Their vision on treatment and their struggles
4. Workload of their profession
5. View on E-health technologies and the integration of them

Results

Guidelines and protocols

Physiotherapists in the Netherlands follow rehabilitation guidelines established by the Koninklijk Nederlands Genootschap voor Fysiotherapie (KNGF) for knee rehabilitation. If patients did undergo surgery or other medical intervention a protocol from the hospital is made stating what is done and how to proceed rehabilitation.
These guidelines provide a structured framework and measurement instruments but allow for flexibility based on individual patient needs. One physiotherapist stated:
"the guidelines give a good indication for rehabilitation processes; however, each person is different physically but also in their personality".

Personalization and patient motivation

medical professionals all had experience with having to slow down a patient and having to encourage or guide a patient for example a physiotherapist stated:
"Sometimes I really have to sit down with a patient and explain the consequences if they go to fast while for other, I need to break things down in smaller steps or showing them that they can do something under supervision".
Furthermore, the goals of the patient require adjustments in making a treatment plan.

Load VS capacity

A fundamental principle in rehabilitation is balancing load versus capacity, which involves assessing a patient's physical abilities and determining the appropriate treatment intensity.
The CLUKS model (coordination, flexibility, endurance, strength, and speed) is commonly used to evaluate and tailor rehabilitation plans in the Netherlands. A psychotherapist stated: "A common tool I use is CLUKS to asses a patient's capacity, this helps me decide what load this patient can handle in this situation" Important to know is that these factors can be influenced by physical limitations but also by mental issues. A rehabilitation docter in secondary care stated: "Factors such as fear or stress can have influence on coordination of muscles and reaction speed. Mental strength can greatly influence endurance and strength"

Standardized protocols to personalized care

While early stage rehabilitation follows standardized protocols, later stages require more personalized approaches one physiotherapist noted.
"In the early stages the procedure for patients is quite similar but later in the process the differences in patients increase depending on goals and commitment to rehabilitation".
Adapting treatment plans to individual progress is a challenge, particularly when managing multiple patients with varying needs and limited time.

Influence of medical history

Professionals emphasize the importance of medical history in treatment planning. Factors such as medication use, pre-existing conditions (e.g., heart disease), and psychological state influence recovery or Illness beliefs (how patients perceive their condition), significantly impact their rehabilitation progress. Therapists use self-reported scales to assess perceived ability in daily activities, such as walking and stair climbing.
"I let a patient do an exercise like walking back and forth then I ask how they perceive their own walking ability on a scale from 1-10. If a patient give a score that is not inline with the reality of their ability it can indicate a cognitive issue, I need to give attention"

Comparison with the " healthy knee"

A benchmark that is used often in rehabilitation is comparing the injured knee to the patient's healthy knee. Metrics such as strength, range of motion (ROM), and functional adaptations help determine progress. One surgeon highlighted: "It's not just about regaining motion it's about ensuring the knee functions well in real life scenarios, considering the full motion of the body."
Surgeons are less close to the rehabilitation process of the patient. However, this often makes it hard for them to quickly access proper treatment. An orthopaedic surgeon stated:
"I will always look at the best possible treatment fitting the goal of the patient and prevent complications, therefore, I communicate the option I recommend to the patient and help them make a choice".

Patient education

Education plays a vital role in rehabilitation. Professionals inform patients about their conditions, treatment options, and preventive strategies. This is particularly relevant for athletes returning to sports, where injury prevention techniques such as stretching and proper warm-ups can reduce the risk of reinjury.

Workload challenges

Medical professionals experience a high workload and that's why many physiotherapists are leaving the field, a former physiotherapist stated:
"I enjoyed helping people, but it is a demanding job and I didn't see much potential in growing, therefore I decided to help people by starting a company and encourage people to move more".

Patient self-management and technology use

Effective communication is critical for understanding patients in a short consultation window, especially regarding their mental state. Administrative tasks like paperwork and medical database entries consume significant time, reducing opportunities for direct patient interaction. Because of the shortages in physiotherapist in the Netherlands patients often require to do more at home. A physiotherapist explained:
"With the high pressure on the healthcare system, patients are required to do more on their own. Having technology to relieve some of that pressure and keeping quality is highly relevant".

E-Health and Wearable Technology in Rehabilitation

When medical professionals were asked about their perspective on E-health and how a wearable device could support knee rehabilitation they often see the potential of it but also had concerns. Many physiotherapists explained that they used devices like leg presses with extra options and other equipment like dynameters to measure muscle strength and pain-relieving machines like ultrasound or massage machines with vibration and heat. These tools are great to have to help patients with pain and also determine if they are ready for the next phase in their rehabilitation.
E-health offers several benefits like improved accessibility to healthcare by decreasing workload or work more efficiently and facilitate telerehabilitation, faster interventions, improve patient engagement and pain management. Furthermore, it can be easier to provide and collect information outside clinical hours.
When discussing the wearable solution proposal many medical professionals explained they would find it important that adherence to home exercises increases and communication about illness beliefs is open. Seeing what happened and how patient reflected on their own ability would help medical professionals to adjust treatment accordingly and save time on performing these tasks while making more time for actually assisting the patient with their issues.
However, there are concerns about overdependence on data, which can undermine patients' trust in their own bodies. One professional compared this to "seeing rain outside but still checking the weather app if it rains." This can lead to insecurity in the long term.

Integration with Braces and Taping

Medical professionals were asked if the wearable design should account for other wearable tools such as braces or taping. Physiotherapist explained it depended on the situation. In the early stages healing is prioritized over movement and sometimes restricted by a brace. But in later stages bracing and taping is not preferred by physiotherapist because of overreliance on a tool. One physiotherapist stated:
"I recommend people to use taping or bracing only when absolutely necessary or as psychological support tool. I encourage patients to strengthen their muscles around the knee in such a way that the muscles become their brace"

Discussion

The findings show the structured yet flexible approach to knee rehabilitation in the Netherlands, where physiotherapists adhere to KNGF guidelines while tailoring treatment to individual patient needs. A key challenge identified is the balance between standardized rehabilitation protocols and the necessity for personalized interventions based on factors such as physical ability, psychological state, and patient motivation. Managing load versus capacity is at the core of what physiotherapists do assessing someone's capabilities and putting a load on them to help them overcome injury. The CLUKS model serves as a widely accepted tool to assess rehabilitation progress.

A great deal of physiotherapists work is understanding how patients perceive their own injury (illness beliefs). Therefore, trust and communication are key for successful rehabilitation. Good trust also establishes a good ground for education of the patient about their treatment plan, options in rehabilitation, goal setting and how to overcome psychological hurdles.

Another theme that emerged is the impact of workload on medical professionals, particularly physiotherapists, which has contributed to a shortage in the field. The increasing demand for self-management among patients highlights the potential role of technology in alleviating some of this burden. E-health solutions, including wearable devices, were recognized as promising tools for improving adherence to rehabilitation exercises, facilitating remote monitoring, and enhancing patient engagement. However, concerns were raised regarding the potential overreliance on data, which could reduce patients' trust in their own physical sensations and abilities. This suggests that while technology can provide valuable support, it should complement rather than replace traditional rehabilitation methods. Furthermore, the integration of wearable technology must consider how information is presented to patients to avoid increasing insecurity or dependence on external feedback.

Conclusion

The qualitative interviews with medical professionals show how personalized the approach to knee rehabilitation is. The introduction to organisations like KNGF and guidelines and phenomenon's like CLUKS, load versus capacity management and illness beliefs will be valuable guidelines to design a wearable solution. Physiotherapists find engagement and mental well being far more important then detailed physical measures.

The findings suggest that designing a wearable solution for knee rehabilitation requires careful integration of both physical and psychological factors. The device should support patient adherence to rehabilitation exercises while fostering confidence in their physical abilities rather than creating overdependence on data.

Given the shortage of physiotherapists and the increasing demand for self-management, wearable technology should enhance efficiency for medical professionals by facilitating remote monitoring and enabling more personalized treatment adjustments.

The device should also account for individual differences in motivation, perception of progress, and psychological barriers such as fear or stress, which can impact recovery. Additionally, it must integrate effectively with existing rehabilitation tools, measurement tools for illness beliefs (questionnaires).

By providing meaningful feedback on progress and facilitating communication between patients and medical professionals, the technology can help bridge the gap caused by limited consultation time.

Ultimately, the wearable solution should serve as a supportive tool that enhances rehabilitation outcomes while maintaining the principles of patient-centered care.

Similar companies

In order get an idea of the market for physiotherapy I visited MEDICA 2024, a large medical fair in Dusseldorf Germany. During these conversations no audio was recorded because of the loud environment. The goal of this visit was to speak with companies that use technology in physiotherapy. Below three relevant companies are described where I spoke with the representatives of these companies and tried their products.

Eularia provides a solution for home exercise guidance using IMU sensors attached to the body. For knee rehabilitation, they use two or three sensors (on the thigh, shin, and sometimes trunk) that interact with a software platform. Physiotherapists can adjust exercise plans through a dashboard, while patients use a tablet interface for guidance.
Strengths include their focus on medical approval for software and their patented magnetic sensor-strap connection. However, I noted difficulties in correctly attaching the sensors, which lacking clear alignment cues, and the high cost of the hardware package (€1,899) limits accessibility.
QuicklyPro offers gait training for patients with walking disabilities using light projection. Patients wear devices on their shins that project dots for their next steps. When I tried the device on the fair the intuitive design requires minimal explanation, but the stepping on the light projections in front of me felt a bit awkward at first because the dot disappears when you step on it, and the devices felt bulky.
BTS Bioengineering develops wireless EMG systems for multiple use cases like medical rehabilitation and sports, such as the FREEEMG. These lightweight probes monitor muscle signals and transmit data for analysis, supporting rehabilitation and injury prevention. The sensors are versatile, even functioning underwater. However, proper placement requires professional expertise to ensure accurate signal detection the representative explained.

Visiting the fair gave me insights into what is developing in the market and provided a foundation for a competitor analysis later in the study. Furthermore, seeing what technologies where being developed provided inspiration for integration of technologies like IMU and EMG sensors in the wearable solution design.

Me trying new developed physiotherpay device

Experts

Having spoken with patients, medical professional and some companies more detailed information about financial viability of the product, measuring human knee movement and sensor integration was still required therefore experts in these fields were consulted to gather more information about the financial side of the knee rehabilitation, how I should approach the biomechanics of the knee for my application and how I could integrate sensors in a wearable while keeping readings accurate.

Insurance consultant (ASR)

The insurance consultant highlighted the increasing cost of healthcare and the growing emphasis on preventive measures. They referenced the "Diagnose Behandeling Combinatie" (DCB), a categorized list of healthcare procedure costs, which could be a useful resource when determining the costs of support devices.
ASR has introduced a prevention app called De Zorg Voor Jezelf App, which offers discounts on insurance premiums for users who adopt a healthy lifestyle. The app also provides tips on prevention, nutrition, and symptom checking. ASR's ideal scenario is to prevent treatments altogether, with the next best outcome being to restore patients to normal health safely and without complications.
Insurance coverage for physiotherapy is often included in additional packages, while secondary care such as referrals or hospitalization is part of the basic package. For support devices to be insured, there must be substantial medical evidence demonstrating that they make recovery faster, safer, or more effective, ultimately reducing risks for the insurer.

Biomechanical Expert

The biomechanical expert, specializing in aging and its effects on biomechanics, conducts research using predictive computer simulations validated through sensor-based user testing. They noted that knee movements can be modelled with varying levels of complexity, ranging from simple flexion and extension to more intricate simulations incorporating internal/external rotation and abduction/adduction. For initial studies, they recommended focusing on flexion and extension.
Regarding knee health, the vastus medialis oblique (VMO), a key quadriceps muscle, plays a significant role in maintaining knee longevity. They emphasized viewing the body as a functional unit, where the knee interacts closely with the hips and feet. Issues in one area, such as a poor gait pattern or compensations in the hips or feet, can lead to knee problems. As the body ages, its capacity to adapt to pain or discomfort diminishes, often resulting in movement related issues. The experts explained:
" We know that the body adapts to our lifestyle, A good example is astronauts that have adjusted to zero gravity, when they return we see reduced bone density and other adaptions, when we experience injury our body does similar adjustments to prevent pain and discomfort".

Sensor Integration Expert

The sensor integration expert, working at the TU Delft, provided guidance on incorporating sensors into textiles, emphasizing that sensors should be lightweight to avoid causing tension on the clothing. Additionally, textiles should be snug enough to minimize sensor movement. They highlighted potential challenges with inertial measurement units (IMUs), such as vibrations caused by muscle activity, which can be mitigated using filters.
For rehabilitation purposes, the expert recommended starting with IMUs and possibly incorporating electromyography (EMG) sensors, while avoiding overcomplicating the setup. Alternatives to IMUs include textile sensors; however, IMUs are a proven technology and thus a better starting point. The expert advised testing sensors early in the design process to assess their response to being worn, as making textile sensors functional could require significant development effort.

Speaking with these experts on insurance, biomechanics and sensor integration in textiles resulted in considerations and requirements for the wearable solution.
In order to get such a device insured for patients it needs to show, in clinical testing, that the device is making knee rehabilitation more effective, safer, cheaper and ultimately involve less risk for complications or reinjury.
Biomechanical important factors to measure during knee rehabilitation and long-term health are knee flexion and extension, supporting muscles like the VMO and the consideration of the whole kinematic chain.
For sensor integration in knee wearables it is important to keep them lightweight and choose garments that are not too loose. Furthermore, testing sensor integration early on in the design process can give insights into how the sensor reacts to being worn and can reveal challenges like muscle movement and vibrations early on.

Conclusion

The qualitative interviews were conducted to gain valuable insights into complexities of knee rehabilitation from perspectives of patients, medical professionals and experts on knee rehabilitation and the use of technology in this process.

Patients showed the mental and emotional challenges they faced overcoming their physical injury like decision fatigue, fluctuating motivation levels and psychological hurdles to overcome. Trust in healthcare providers, support systems, and access to meaningful progress tracking were key factors influencing their rehabilitation experience. While some patients benefited from strong social support, such as being part of a rehabilitation group, others felt pressured by comparisons, affecting their confidence and adherence to recovery plans.

Medical professionals showed that treatment plans have guidelines but emphasize the balance between the protocols and personalisation of the recovery. They acknowledged the role of psychological factors in recovery, particularly how illness beliefs and motivation influence progress for optimal load versus capacity management.
The high workload in physiotherapy increases the need for efficient tools, with wearable technology offering potential benefits for remote monitoring and patient engagement. However, professionals had concerns about overdependence on data, which could reduce patients' trust in their own body and decision making.

Visiting the MEDICA 2024 medical fair has provided information about viability and market developments while giving inspiration for sensor use and product development.
Expert insights have resulted in valuable requirements and tips regarding insurance coverage, biomechanics measurements of the knee and sensor integration.
For insurance coverage the wearable should make rehabilitation more effective, cheaper or safer with clinical proof.

Tracking the biomechanics requires consideration of the whole kinematic chain, while knee flexion and extension is most commonly tracked activation of muscle groups can be useful to ensure proper muscle engagement during exercise and prevent overloading. Furthermore, adaptions of the patient should be taken into account.
Wearable sensor solutions should be lightweight and early testing of integrated solutions can expose challenges early on.

Concluding, a successful wearable must not only provide actionable feedback and progress monitoring but also needs to support communication between patients and medical professionals, addressing both physical and psychological aspects of rehabilitation.

1.3. Stakeholder analysis

In the design process for a knee rehabilitation wearable, understanding the needs and expectations of stakeholders is essential. This stakeholder analysis identifies the wants and needs of all involved parties through a combination of literature review and stakeholder interviews, see 1.2. qualitative interviews. By evaluating the importance of each stakeholder in relation to the product design process, this analysis distinguishes between primary and secondary priorities, ensuring that the most critical requirements are addressed effectively. This approach lays a foundation for creating a product that aligns with stakeholder expectations. For stakeholder importance a stakeholder map was created, see figure 6.

In this design process, the most important stakeholder is the patient. The product is worn and used by the patient. The physiotherapist or a more specialized rehabilitation doctor is often the main caregiver and needs to interact with the product, as it would display measurements or statistics relevant to the patient's progress. Therefore, they are a close second in priority. General practitioners and orthopedic surgeons are frequently involved in the patient's journey, making their needs the next consideration. Other stakeholders, such as insurance companies, must also be taken into account, as they influence the healthcare landscape and impact the patient's resources, including time, money and emotional state.
The stakeholders in figure 6 will be decribed on the next page. The rehabilitation doctor and psychiotherapist have indentical wishes and requirements therefore these two have been merched in the description.

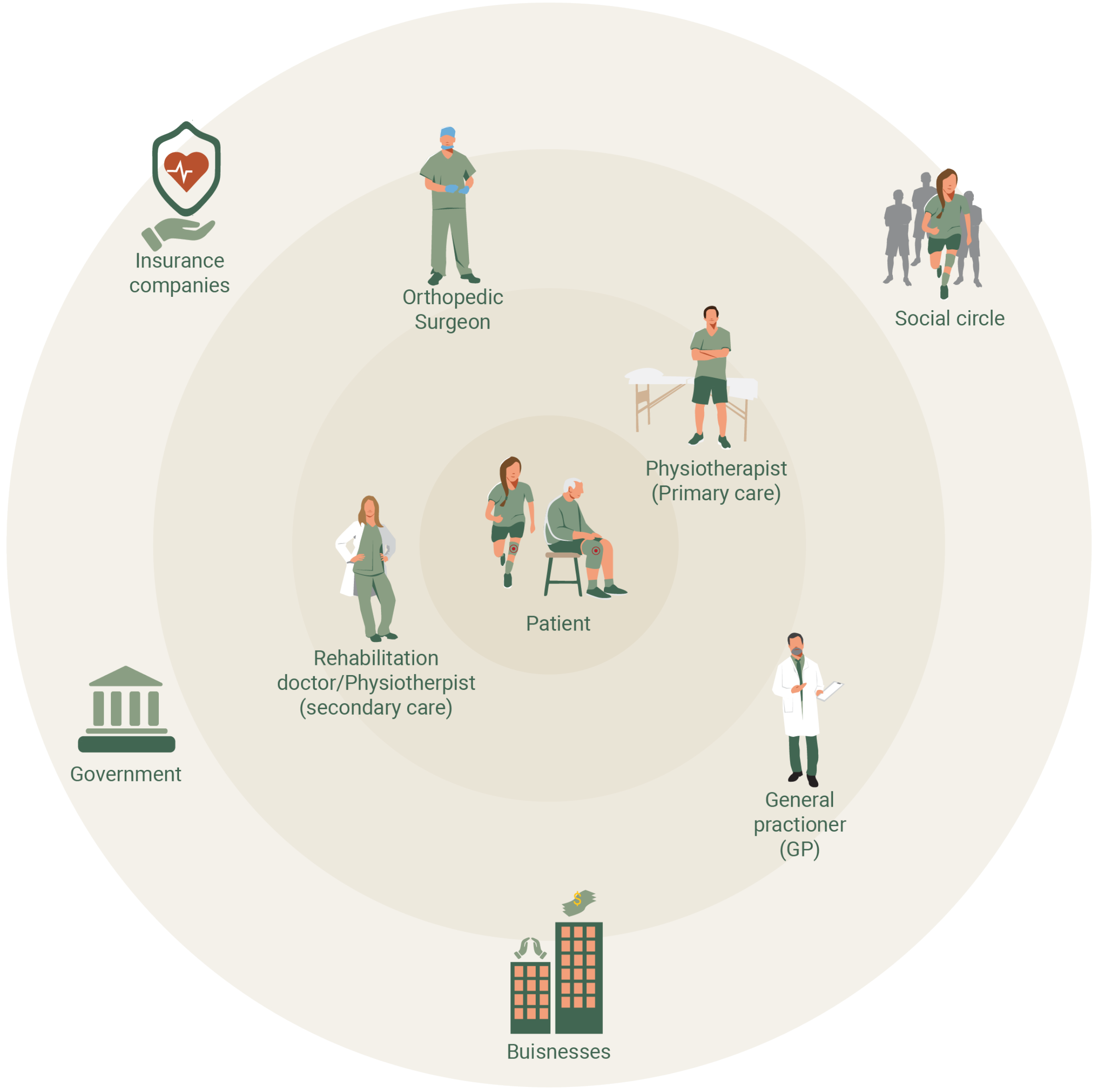


Figure 6: Stakeholder analysis

Patient

Patients seek a process that is effective, supportive, and minimally disruptive to their lives. They value accessible, affordable care options like online sessions, nearby clinics, or flexible schedules that fit their routines. Managing pain, building confidence, and regaining independence are key goals. Feeling heard by healthcare providers and having clear communication about their progress and recovery options foster trust and collaboration. Support from family and friends is essential, offering encouragement and reducing isolation. Ultimately, patients want a personalized, cost-effective plan that respects their time, promotes healing, and helps them return to normal life physically and mentally.

Physiotherapists & Rehabilitation doctor

Physiotherapists are essential to rehabilitation, providing guidance beyond injury assessment and treatment planning. They often become trusted partners for patients. However, administrative tasks like paperwork reduce the time available for direct patient care. Streamlining these processes could help them focus on what matters most.
Through my interviews, I found that physiotherapists prioritize psychological factors, such as patient motivation, understanding, and consistency, over clinical metrics. They emphasized keeping patients engaged and confident during recovery. Similarly, a study on gamified rehabilitation devices (Qiu et al., 2021) found psychological aspects highly valued by physiotherapists.
E-health solutions like telerehabilitation were also discussed. While appreciated for accessibility, physiotherapists expressed concerns about patients over-relying on technology, potentially reducing confidence in self-management.

Orthopaedic surgeon

Orthopaedic surgeons seek reliable information about a patient's post-surgical recovery to ensure effective healing and reduce the risk of complications. Their primary goal is to improve patient outcomes by tracking progress and intervening if needed. Collaboration with rehabilitation professionals is important to align surgical and rehabilitative goals. They value approaches that minimize re-injury rates and support a clear path to recovery.

General practitioner

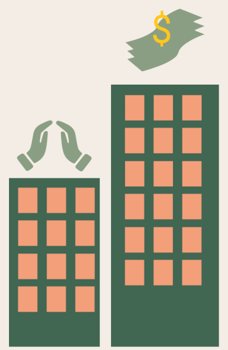
General practitioners are focused on holistic patient health, including injury prevention and early intervention. They want effective ways to assess injuries and track patient recovery over time. Ensuring that care is coordinated and that patients receive appropriate guidance and support are key priorities for GPs, as they often oversee the patient's long-term health journey.

Social circle

Patients social circles want to see their loved ones recover fully and regain their usual activities. They value being able to offer support in ways that are meaningful and helpful. Understanding the rehabilitation process and having clarity about their role in it is important to these stakeholders, as it helps them provide emotional and practical assistance.

Insurance companies

Insurance providers prioritize cost-effective healthcare solutions that deliver measurable results. They seek evidence that rehabilitation processes are efficient and successful, leading to fewer claims and reduced overall expenses. In the Dutch healthcare system, the expenses for insurance companies are determined by the DBC (Diagnose Behandeling Combinatie) cost for treatment (JBZ, 2024). These costs increase significantly if complications or setbacks occur during rehabilitation.
If a product can reduce complications and risks, it may be recommended, encouraged, or even insured for patients, enhancing its adoption and accessibility within the healthcare system. Preventive care measures that lower the likelihood of future injuries are particularly valuable to insurers. For example, A.S.R., a Dutch insurance company, offers a mobile app called De Zorg Voor Jezelf App, which provides tips on prevention, nutrition, and symptom checking (2024).
Physiotherapy, however, is often only covered as an additional service, requiring customers to pay higher premiums. Transparent reporting on treatment outcomes is critical for insurers to evaluate the effectiveness of interventions and make informed decisions.



Buisineses

Employers
Employers prioritize efficient recovery processes to help employees return to work in good health, minimizing disruptions while supporting recovery. Preventive measures that reduce future injury risks enhance productivity and promote employee well-being. Large institutions, like the Dutch military, include physiotherapy in employee benefits, covering rehabilitation costs (Ministerie van Defensie, 2023). By focusing on care, cost reduction, and risk mitigation, employers aim to ensure safe and timely workplace reintegration.

Device Manufacturers and Selling Companies
Health technology companies focus on creating effective, trusted solutions that comply with ethical standards and regulations. Their goals include improving healthcare outcomes, safeguarding data privacy, and building strong relationships with providers and patients to maintain market presence.

Governments

Governments prioritize public health improvements and seek solutions that enhance population mobility while reducing healthcare expenditures. They value interventions that promote preventive care, minimize reliance on in-clinic treatment, and enable patients to recover at home with support of their social circle and neighbourhood. Ensuring compliance with data protection standards and maintaining patient safety are key considerations.

1.4. Patient journey

Understanding the patient journey is important for creating a suitable solution, as the challenges encountered shape how patients and stakeholders perceive the rehabilitation process. To explore this journey, interviews with stakeholders on knee rehabilitation processes were conducted, see 1.2. , and analysed for common themes along with a literature review on rehabilitation processes (Wright et al., 2015; Bedi et al., 2021; Grindem et al., 2016; Sarraj et al., 2019). To simplify the findings, I created a patient journey map, providing an overview of key activities and challenges, see Figure 7 and the detailed map in Appendix C. The map is divided into coloured stages:

1. **Injury**
2. **Seeking help, diagnosis**
3. **Prehabilitation, medical intervention**
4. **Normalizing movement, strengthening, functional training**
5. **Return to normal activity**
6. **Re-injury**

Knee rehabilitation is highly individualized, with journeys varying based on injury severity and patient goals. For less severe injuries or modest goals, surgery or intensive interventions may not be needed. Therefore, some patients skip these steps in the patient journey.
Injuries are categorized into primary or secondary care. Primary care is less intensive and typically accessed without referrals, whereas secondary care often requires a referral (except for emergencies).
The patient journey map outlines activities, emotions, pain points, stakeholders, and opportunities at each stage. Based on my interviews and medical protocols, the ideal progression (green line) shows gradual improvement after seeking help, with minor setbacks during healing after interventions, followed by steady recovery through appropriate stimulation.
The detailed findings and explanation of reoccurring themes can be found on the next page.

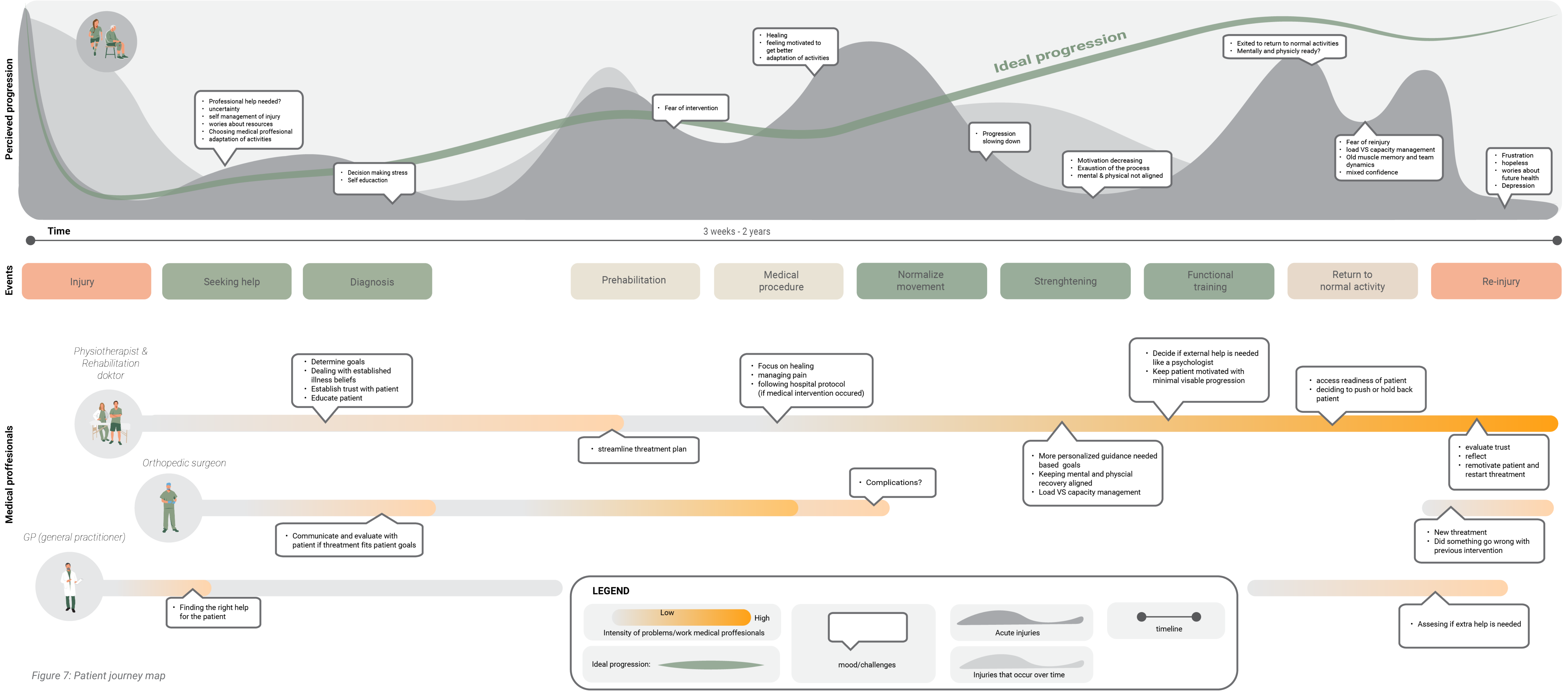


Figure 7: Patient journey map

Themes in the rehabilitation journey

Making the patient journey provided some key insights and continuities with all knee rehabilitation processes. These themes are important to consider before making a product:

Load VS capacity

An important concept in rehabilitation is the balance between load and capacity, a principle also used in sport science. Physiotherapists carefully adjust the amount of physical effort they ask patients to handle based on medical history and condition. The goal is to challenge patients enough to help them improve without causing new injuries or re-injury. At the same time, they consider the patient's mental view of their own ability (illness beliefs). Sometimes patients believe they can handle more than they actually can, while others underestimate their capacity, see figure 8. Physiotherapists work to help patients align these perceptions with their actual physical abilities, deciding whether to push them harder or ease off to avoid setbacks.
This balance between physical and mental factors is at the heart of what physiotherapists do, showing just how complex and personalized knee rehabilitation actually is. Teaching proper Load versus capacity to patients plays a vital role in injury prevention, teaching proper warm-up routines, stretches can increase long term joint health and resilience against future injuries.

Illness beliefs and communication

It is important for medical professionals and patients to communicate their beliefs about the injury. Therefore, classic measurement instruments have been developed by medical professionals and scientists, as described by the KNGF (Meetinstrumenten in de zorg, n.d.). Many of these instruments involve questionnaires with questions such as evaluating how certain activities, like walking, are perceived by the patient on a scale of 1 to 10. These scales help medical professionals understand illness beliefs.

Personalisation

Rehabilitation programs are often highly personalized. During the lifetime of the human body, the body adjusts to the activities and posture during its loading on earth. Therefore, some aspects are more developed than others. Some extreme examples are a powerlifter and a marathon sprinter, who both have developed very different adaptions to perform, one is more adopted for explosive power in short amount of time while the other has a body more adapted for endurance. Or astronauts having to constantly train because of their body adaptions to zero gravity. This principle also applies in smaller adaption: always having more internal rotated knees or external rotated knees. Taking this Principle into account is crucial and means that a weird move is not always bad if the body is adjusted to it, of course each adaption can come with a risk or cost of other movement, therefore evaluating the body for these adaptions is important because it effects the treatment plan.

Education & trust

During interviews, patients have stated that they had limited knowledge about their issue. Which results in that making decisions can be scary. Therefore, trust in medical professionals and laying out the options and listening to the patient is critical for adjusting treatment plans.

Social involvement

If you get injured from a sport or are less mobile due to physical complaints, having a social circle that is assertive greatly impacts rehabilitation. During my own interviews, patients made the point of meeting people with the same injuries and being understood and progressing together helped greatly in the rehabilitation process. Furthermore, having a supportive social circle can prevent isolation and loneliness, help in daily chores, transport to medical appointments. However, some patients also mentioned the danger of comparisons with other people. "I saw everyone get better and I was left behind ".

Self managing and mixed confidence

After rehabilitation patients return to normal activity, often with knee injuries, maintenance is required to prevent re-injury or worsening conditions. Staying consistent in these maintenance programs can be difficult to self manage, especially if the trusted physiotherapist is not there anymore to give them feedback.
Some injuries like the ACL and ACLR often have a high risk of re-injury especially in the early years after rehabilitation. This can result in doubt, concerns and fear in rehabilitation and returning to normal activity. Fear of re-injury has a negative impact on rehabilitation (Hsu et al., 2016).

Stages in Knee rehabilitation:

- Restoring range of motion and normalizing movement
- Strengthening the knee and surrounding structures
- Occupational specific functional training

During the first stage the priority is healing and keeping the joint flexible. This is relatively the same for all patients and here is the most overlap between different knee injuries although the timeframe differs. During the second and third stage rehabilitation processes can differ a lot more depending on goals of the patient. During rehabilitation the injured knee is often compared to the healthy knee to ensure symmetry and proper loading of both legs.

In short, the knee patient journey is a highly personalized and complex process. Managing all the different factors in the physical but also the psychological side in the journey is hard. Therefore, the importance of professional medical assistance in the use of support devices is very important. Because the options and conclusions about recovery are almost never binary and involve a lot of choices from the patient and medical professionals.

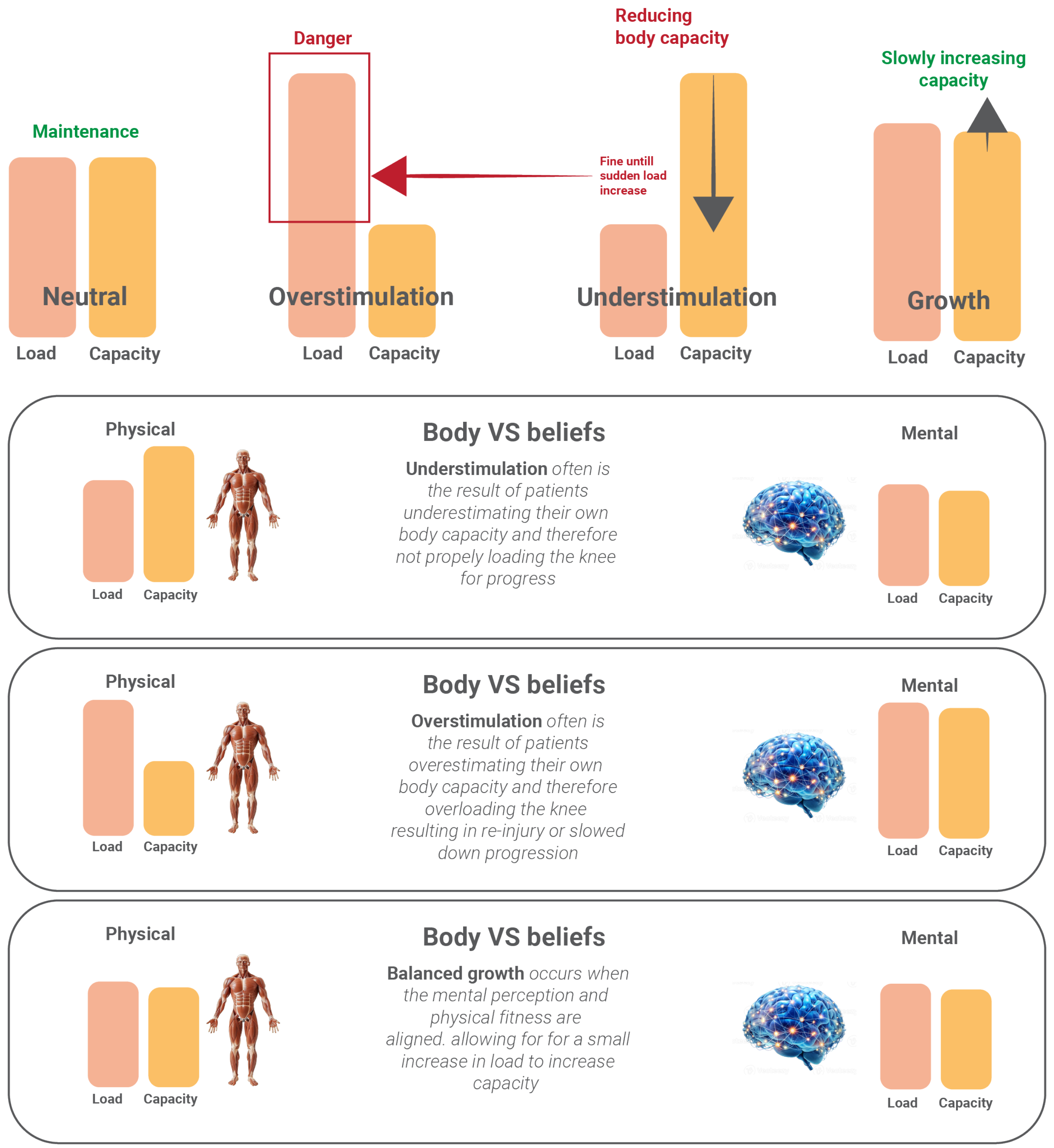


Figure 8: Load VS Capacity

Medical attention and diagnosis

How medical attention and the diagnosis of the patient is done can provide better insight into medical proffesional contribution and parameters used.

Seeking professional help

The journey of the patient starts with the patient experiencing symptoms of knee pain. This can be a sudden event where an external force or a wrong move creates an acute problem, but it can also be symptoms that slowly occur over time. Determining why and when people seek help in their knee rehabilitation is complicated and depends on the following seven factors described in table 3 (Morden et al., 2014). Looking at these factors it is clear that people with an acute knee injury will seek help sooner if not directly after the incident depending on the severity while people with slowly increased knee pain may wait longer to seek help.

Factor	*explanation*
Perceived severity and disruption of pain	*People seek help when the knee pain becomes/is severe, unmanageable or disrupt quality of life.*
Beliefs about treatment efficacy	*Scepticism of what a healthcare professional can offer can prevent people from seeking help*
Social influence and normalization of pain	*Family and friends can greatly influence the decision to seek help, they can encourage it but, can also normalize symptoms for reasons like aging*
Self responsibility and resources scarcity	*Patients can see medical professional help only as a scarce emergency resource and avoid it except absolutely necessary. Seeking help is sometimes an investment which can also influence people's decision to seek help.*
Past medical interactions	*A past experience with healthcare professionals (positive and negative) can influence consulting a healthcare professional again.*
Social and Moral judgement	*Patients can compare the severity of their injuries to the people around them and judge if its "worth" consulting a professional.*
Exhaustion of self management strategies	*If patients have tried self managing their injury and they have run out of solutions, they often seek help.*

Table 3: The factors that influence people to seek professional help in knee rehabilitation (Morden et al., 2014).

Diagnosis

Understanding the diagnostic process is crucial for appreciating the initial parameters used by medical professionals to formulate treatment strategies. By integrating the patient's subjective account of their injury with objective physical findings, clinicians gain a holistic understanding of the patient's condition, enabling more effective treatment and rehabilitation planning.

The diagnosis of knee injuries involves three critical elements: a discussion of the patient's history, a detailed physical examination, and determining the specific type of injury, followed by appropriate further investigative steps such as referral to a specialist or imaging studies like MRI. (Austermuehle et al., 2001)

The process typically begins with understanding the patient's history through a comprehensive conversation. This initial discussion helps the clinician gather essential details about the injury and its context. Key questions include when and how the injury occurred, whether it is associated with a specific activity, and how the patient describes the pain in terms of onset, duration, location, and severity. Additional inquiries focus on the degree of dysfunction or disability the patient is experiencing, previous treatments and injuries, and any medications or substances the patient may be taking.

In cases of acute injuries, the clinician seeks to understand the circumstances surrounding the injury. For instance, was the injury caused by an external force, such as a collision, or did it result from an individual's movement, such as landing awkwardly from a jump, twisting, or sudden deceleration? The position of the lower limb at the time of injury can also provide valuable clues. Acute knee injuries frequently involve ligament damage, such as tears to the anterior cruciate ligament (ACL) or medial collateral ligament (MCL). Additionally, issues with the meniscus are common. The causes and symptoms of these injuries are discussed in greater detail in appendix D.

Unlike acute injuries, overuse injuries typically present with a gradual onset of pain rather than a single precipitating event. These injuries may result from extrinsic factors such as poor athletic training techniques or inappropriate footwear, as well as intrinsic factors such as inadequate flexibility, malalignment, or structural abnormalities. Common overuse injuries include patellofemoral syndrome (PFS), knee tendonitis, and, in older individuals, osteoarthritis (OA). The underlying causes and symptoms of these conditions are further elaborated in appendix E.

The physical examination is a vital component of the diagnostic process, allowing the clinician to assess the integrity of the knee's structures through specific manoeuvres. For example, the Lachman test and anterior drawer test can help identify excessive motion in the knee joint, indicating a potential ACL injury. A detailed description of these manoeuvres is available in appendix F. Based on the findings of the physical examination, the clinician may determine whether further evaluation, such as consultation with an orthopaedic specialist or advanced imaging techniques like MRI or X-ray, is necessary.

Concluding, the diagnosis involves talking about patients own perception of the injury, information about the injury, medical history and combining it with physical examination to determine physical and psychological information to determine next steps.

Secondary care

Following an initial examination by a general practitioner (GP) or physiotherapist, patients may be referred to a specialist, such as an orthopaedic surgeon or a radiologist, for further evaluation. In some cases, particularly after severe accidents like car crashes or sports injuries, patients may bypass these steps and be directly admitted to the emergency room. In such situations, immediate medical intervention may be necessary.

Medical interventions can range from medication, such as oral pills or injections, to surgical procedures. Surgical options may include ligament reconstruction or, in more severe cases, the complete replacement of the knee joint with a prosthetic. These interventions are discussed in greater detail in appendix G.

The type of medical intervention performed has significant implications for subsequent physical therapy and movement rehabilitation. Physiotherapists often receive specific protocols to follow during the patient's recovery, which are tailored to the surgical procedure or treatment the patient has undergone.

Understanding these medical interventions is therefore crucial for designing assistive devices, such as wearables, that support patients during the healing process and facilitate their recovery.

Important measures knee physical therapy

As mentioned earlier understanding the capacity of the body is very important in order to justify the load the patient can handle. To measure the capacity of the body Dutch physiotherapist and sport scientist use CLUKS which describes five aspects of body capacity. Translated to English these aspects are Coordination, flexibility, endurance, force and speed. To these aspects there are influential factors that can influence these 5 aspects, see table 4.

Aspect	*Types*	*Influential factors*
Coordination	*General (daily activities) & Specific (sport-specific)*	*Nervous system, senses, fatigue, fear, aging, and practice complexity.*
Flexibility	*General vs. Specific, Active vs. Passive, Dynamic vs. Static*	*Inactivity, hormones, age, stress, fatigue, injuries, body composition, and environmental factors.*
Endurance	*Basic, Strength-Endurance, Speed-Endurance*	*Training intensity, recovery, cardiovascular capacity, psychological resilience, and nutrient availability.*
Force	*General & Specific, Static, Dynamic-Concentric/Excentric*	*Muscle coordination, training, injury history, neuromuscular development, and physical structure.*
Speed	*Reaction, Acceleration, Maximum, Speed-Endurance*	*Strength, coordination, alertness, genetics, and mental focus.*

Table 4: explanation of CLUKS (Reactionlights.nl. (2024))

CLUKS is more general approach to physical therapy and can be applied to all rehabilitation processes.

If we look more detailed to knee rehabilitation process. There are some activities and measures patients and medical professionals have to consider during the knee rehabilitation process (Prentice, 2024) (Czamara et al., 2021) (Iwamoto et al., 2007) (Davies et al., 2017):

- Restoring/Maintaining Range of Motion (ROM)
- Increasing Muscle Strength and Engagement
- Managing Inflammation and Swelling
- Balance and Proprioception Training
- Considering the Whole Kinematic Chain
- Ensuring Symmetrical Movement and Proper Gait
- Pain and Discomfort Management
- Psychological Challenges
- Physical Differences
- Considering Medical State and History
- Cardiorespiratory Fitness Maintenance
- Tissue Healing Phases and Rehabilitation Timing
- Scar Tissue and Myofascial Considerations
- Joint Alignment and Biomechanics
- Nutritional Support
- Functional Progressions and Return-to-Play Criteria

Restoring/maintaining Range of Motion (ROM)

Restoring ROM is a primary goal after a knee injury to prevent stiffness and ensure functional movement. Limited ROM often results from swelling, scar tissue formation, or muscle guarding. Early intervention using passive and active stretching, manual therapy, and joint mobilization improves flexibility and maintains tissue elasticity. Techniques like proprioceptive neuromuscular facilitation stretching can increase joint mobility while minimizing discomfort. Achieving full ROM is essential for enabling daily activities and forming the foundation for strength and stability work. Untreated restrictions may lead to compensatory movements, straining other joints and increasing the risk of further injury.

Increasing Muscle Strength and Engagement

Strong muscles protect the knee joint and reduce stress on surrounding ligaments. Rehabilitation emphasizes progressive resistance exercises, beginning with isometric contractions to engage muscles safely. Proper form ensures balanced engagement of quadriceps, hamstrings, and supporting muscles, progressing to dynamic functional exercises. Strength training also enhances neuromuscular coordination, reducing compensatory patterns that could lead to re-injury. Tools like resistance bands, weights, or bodyweight exercises allow tailored and gradual strengthening of the knee.

Managing Inflammation and Swelling

Inflammation and swelling, natural responses to injury, can impede recovery if unmanaged. The POLICE protocol (Protection, Optimal Loading, Ice, Compression, and Elevation) minimizes swelling in early recovery. Ice application reduces inflammation, while compression and elevation facilitate fluid drainage and decrease blood pooling. Managing swelling early prevents complications like joint stiffness or delayed healing, allowing the rehabilitation process to progress efficiently.

Balance and Proprioception Training

Injuries disrupt the body's ability to sense joint position, increasing instability risks. Proprioceptive exercises, including single-leg stands, wobble board activities, and dynamic stability drills, retrain neuromuscular responses. Early incorporation of these exercises improves balance, reaction times, and movement efficiency, promoting a more stable and responsive knee joint.

Considering the Whole Kinematic Chain

The knee is part of an interconnected kinetic chain of joints, muscles, and neural systems. Open kinetic chain (OKC) exercises, such as seated leg extensions, isolate specific muscles but may introduce shear forces on the knee. Closed kinetic chain (CKC) exercises, like squats and step-ups, promote co-contraction of muscle groups, enhancing joint stability and mimicking functional movements. Balancing both types ensures comprehensive recovery while tailoring exercises to the healing phase, injury type, and patient goals.

Ensuring Symmetrical Movement and Proper Gait

Compensatory patterns from injuries can cause imbalances, increasing strain on the uninjured side. Gait training, combined with targeted exercises, restores symmetry and reduces overuse injuries. Tools such as mirrors, video feedback, or gait analysis software help patients visualize and correct abnormalities. Addressing gait issues early minimizes chronic pain, secondary injuries, and joint degeneration.

Pain and Discomfort Management

Effective pain control enhances patient compliance and rehabilitation progress. Cryotherapy, thermotherapy, and electrical stimulation alleviate pain and inflammation. Medications may be used when necessary. Therapists utilize graded activity techniques to ensure exercises stay within manageable pain thresholds. Managing pain effectively motivates patients and fosters consistency in their recovery.

Psychological Challenges

Psychological factors like fear, frustration, or low motivation can hinder recovery. Goal-setting, visualization, and regular communication keep patients engaged. Individual considerations, such as beliefs about the injury or fear of reinjury, should be addressed. Small, achievable milestones rebuild confidence and adherence to the rehabilitation plan, accelerating recovery.

Physical Differences

Rehabilitation programs must accommodate individual anatomical and physiological differences. Older patients may require gentler exercises, while younger, more active individuals might need higher-intensity programs. Gender-specific considerations, such as Q-angle differences, and weight management strategies further personalize recovery plans.

Considering Medical State and History

A thorough medical history review, including past injuries, surgeries, and medications, informs safe and effective rehabilitation plans. Pre-existing conditions and current medications influence healing and pain perception. Collaboration with healthcare professionals ensures a comprehensive approach, addressing all recovery factors.

Cardiorespiratory Fitness Maintenance

Preserving overall fitness prevents deconditioning during knee rehabilitation. Low-impact activities, such as swimming or cycling, maintain cardiovascular health without stressing the knee.

Tissue Healing Phases and Rehabilitation Timing

Rehabilitation aligns with tissue healing phases acute (inflammation control), subacute (mobility and strength restoration), and chronic (functional activities). Timing interventions correctly ensures optimal healing and minimizes setbacks.

Scar Tissue and Myofascial Considerations

Scar tissue and myofascial adhesions can limit mobility. Techniques such as myofascial release, massage, and stretching restore soft tissue flexibility, preventing dysfunction.

Joint Alignment and Biomechanics

Alignment issues, like valgus or varus deformities, increase knee strain. Correcting alignment optimizes force distribution and reduces risks of re-injury or chronic conditions.

Nutritional Support

Nutrition supports tissue healing and inflammation management. Adequate protein intake aids muscle repair, while vitamins C and D and omega-3 fatty acids enhance recovery. Encouraging a recovery-supportive diet optimizes outcomes.

Functional Progressions and Return-to-Play Criteria

Clear return-to-play benchmarks, such as strength symmetry (85–90% of the uninjured side), pain-free functional activities, and sport-specific drills, guide safe progression to normal activity and prevent premature re-injury.

Conclusion

Recovering from a knee injury and maintaining long-term health involves many factors. Key elements include restoring movement, rebuilding strength, and improving balance all essential for helping the knee function properly again. Managing swelling and scar tissue is also crucial to keeping the healing process on track.
It's important to look at how the whole body works together. Correcting movement patterns can reduce the risk of future injuries and support better overall function.
A well designed recovery solution should feel personal. It needs to adapt to each individual's needs, medical history, and personal goals. Comfort and ease of use are essential, along with features that keep users motivated and engaged.
When combined with tools to track progress and monitor overall fitness, a wearable device can go beyond supporting recovery. It can boost confidence, encourage activity, and help people stay healthy and active in the long run.

1.5. Technology in knee rehabilitation

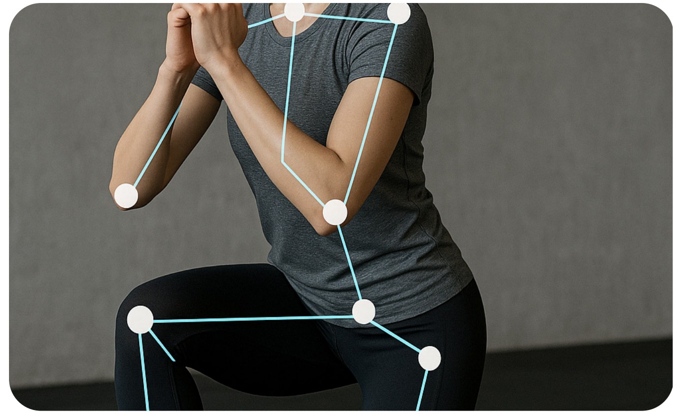
In order to select valuable technologies to solve the problems in knee rehabilitation, it is important to understand the developments of technologies that have the potential to be used in knee rehabilitation. Therefore, a TRL (technology readiness levels) model was created during this project to rate the readiness of technologies for knee wearable use, to spot development trends, and to identify interesting combinations of technological principles for use in the design later. Literature research was combined with an earlier study on technologies in physical rehabilitation (Nascimento et al., 2020) to create an overview (see table 5).

TRL level	*Technologies*
1 (Basic principles observed)	*-*
2 (Technology concept formulated)	*-*
3 (Experimental proof of concept)	*Neural brain Interfaces (like Neurolink), Quantum Computing, Nanoelectronics ((Vaghasiya et al., 2023)*
4 (Technology validated in lab)	*Soft Sensors (Stretchable, Conductive Fabrics), Self-Powered Wearables, AI and Machine Learning for Movement Prediction*
5 (Technology validated in relevant environment)	*GSR Sensors, Advanced Actuators (Ultrasonic, Iontronic), Bioelectrical Impedance Analysis (BIA)*
6 (Technology demonstrated in relevant environment)	*Multi-Sensor Platforms, Wearable Knee Exoskeletons, Light Guided Movement, Marker less Motion Tracking*
7 (System prototype demonstration in operational environment)	*Smart Insoles, Temperature Sensors, Electro-stimulation (EMS), Vibration Therapy,*
8 (System complete and qualified)	*IMU Sensors, Heart Rate Monitoring Systems, Virtual and Augmented Reality, Temperature sensors, EMG Sensors, AI*
9 (Actual system proven in operational environment)	*CPM machine, smart gym machines*

Table 5: TRL model

Marker less Motion Tracking and Video Tracking of the Knee

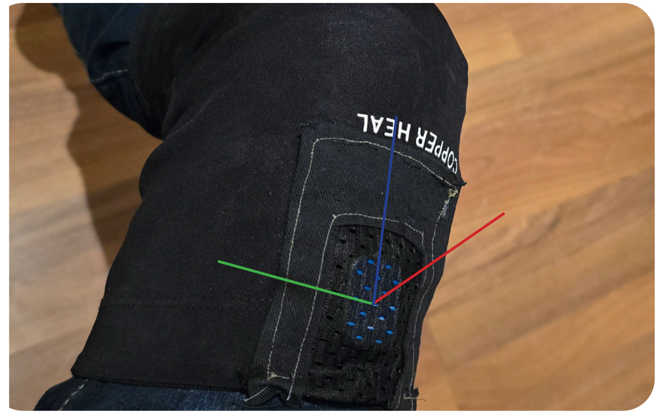
Marker less motion tracking is an emerging technology that uses computer vision and AI to analyse biomechanical movements without the need for physical markers or sensors. This technology has seen increasing adoption in rehabilitation, especially with advancements in machine learning and AI, which allow for real-time analysis of joint motion using camera systems. According to Wade et al. (2022), these systems, whether using single or multi-camera setups, have started to be implemented in clinical rehabilitation, providing valuable insights into patients' knee movements during recovery. One of the key benefits of marker less tracking is that it eliminates the need for specialized equipment, such as markers or wearable sensors, making it more accessible for remote or telerehabilitation settings. However, challenges remain, such as the inability to capture direct physiological signals like muscle activation and the accuracy of the system being compromised by factors like loose clothing or environmental lighting conditions (Wade et al., 2022). Despite these limitations, marker less motion tracking has shown great potential for use in knee rehabilitation, especially when combined with other data, such as EMG or IMU sensors, to provide a more comprehensive understanding of knee function.



Markerless tracking

Inertial Measurement Units (IMUs)

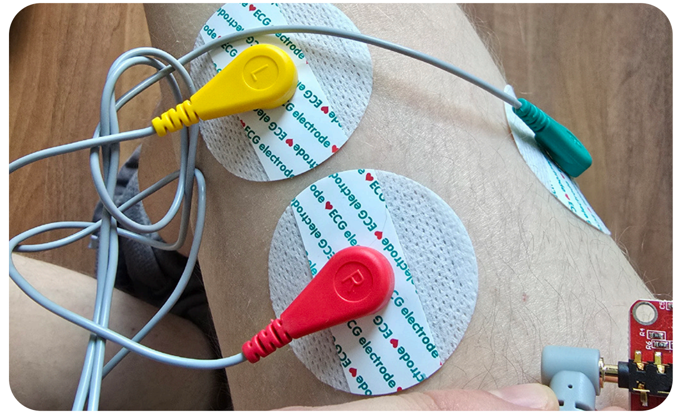
Inertial measurement units (IMUs) are among the most widely used sensors in wearable knee rehabilitation devices due to their ability to measure motion, acceleration, and angular velocity. By combining accelerometers, gyroscopes, and magnetometers, IMUs provide real-time data on knee joint kinematics and gait analysis. One of the key advantages of IMUs is their ability to provide accurate joint angle measurements without the need for precise sensor placement, making them versatile for both clinical and home use. Recent advances, such as quaternion-based alignment methods, ensure that IMUs can be used effectively even in challenging environments like magnetic disturbances or amputee gait (Seel et al., 2014; Vargas-Valencia et al., 2016). IMUs also benefit from machine learning integration, where artificial neural networks (ANNs) can predict joint forces, offering valuable insights into rehabilitation progress (Stetter et al., 2019). Despite their advantages, IMUs do experience signal drift over time, which necessitates regular recalibration and correction methods to maintain data accuracy. However, their affordability, portability, and ability to monitor complex movement patterns make them an essential tool in rehabilitation.



IMU's

Electromyography (EMG) Sensors

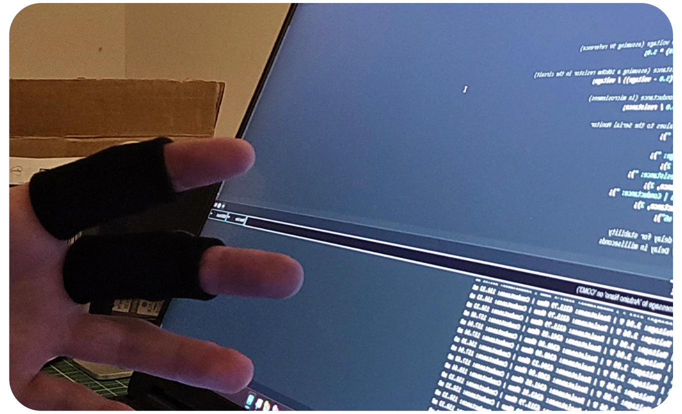
Electromyography (EMG) sensors are used to monitor muscle activity by detecting the electrical signals that muscles generate during contraction. These sensors are particularly beneficial for knee rehabilitation, as they provide detailed information on muscle activation patterns and fatigue, which are key factors in rebuilding strength and function post-surgery. EMG sensors, when integrated with IMUs, offer a more comprehensive view of knee biomechanics. For example, Malesevic et al. (2023) demonstrated how combining IMUs and EMG sensors achieved 0.95% accuracy in a controlled lab setting, providing data on both joint angles and muscle activity. This integration allows for more precise monitoring of isometric exercises and overall muscle performance. Despite their potential, EMG sensors still face challenges in wearable applications, such as discomfort and the complexity of data analysis in real-time. However, when properly implemented, EMG sensors provide crucial feedback on muscle engagement, helping clinicians and patients avoid overexertion and tailor rehabilitation exercises effectively.



EMG

Galvanic Skin Response (GSR) Sensors

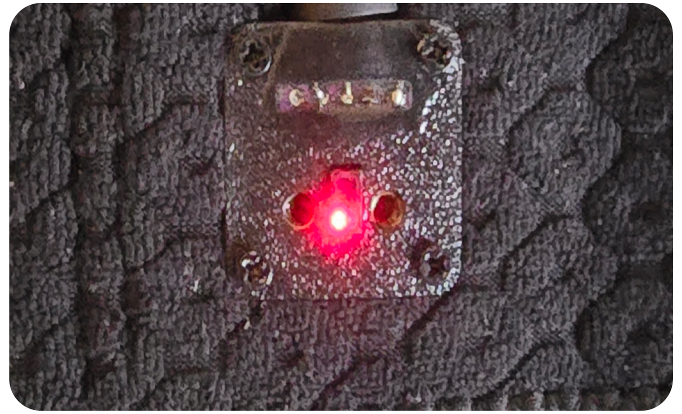
Galvanic skin response (GSR) sensors are used to measure changes in skin conductance, which occurs due to sweating, a physiological response to stress, pain, or emotional arousal. This makes GSR sensors particularly useful in tracking pain levels during rehabilitation. Aqajari et al. (2021) developed an innovative algorithm to assess pain intensity through GSR, which could be particularly useful for wearable devices designed to monitor patients during rehabilitation. The main benefit of GSR is that it provides real-time, non-invasive data on emotional arousal such as pain and stress, allowing for adjustments to rehabilitation plans as needed. However, the accuracy of GSR can be affected by external factors such as anxiety or stress, and distinguishing between different pain intensities can be difficult, especially in dynamic rehabilitation environments. Nonetheless, when integrated with other sensors like heart rate variability (HRV), GSR sensors could offer more accurate and reliable feedback for managing pain in knee rehabilitation.



GSR sensor

Heart Rate (HR) & Heart Rate Variability (HRV) Sensors

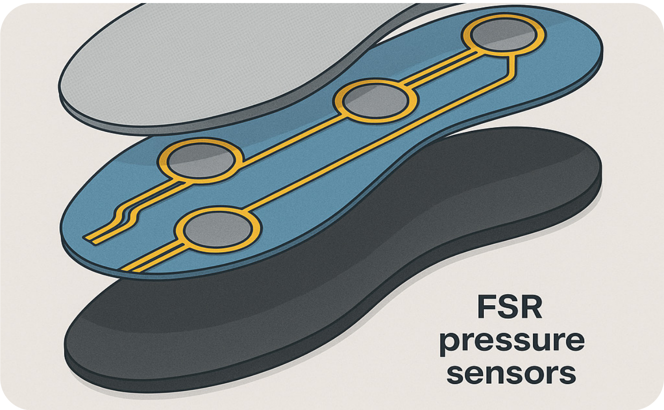
Heart rate sensors and HRV measurements are commonly used in wearable devices to monitor cardiovascular health and recovery. HRV, in particular, is an important indicator of autonomic nervous system balance and recovery status. For knee rehabilitation, HRV offers valuable insights into how well the body is responding to rehabilitation exercises. Studies have shown that HRV can improve during passive recovery sessions, such as CPM therapy, especially when combined with non-invasive interventions like music (Hsu et al., 2017). The ability to monitor HRV allows clinicians to tailor rehabilitation intensity based on individual recovery needs, preventing overexertion that could lead to re-injury. However, HRV can be influenced by a wide range of factors, including sleep, nutrition, and stress levels, which complicates its interpretation. Integrating HRV with other sensor data, such as muscle activity and pain levels, would improve its accuracy and utility in clinical practice (Olivier et al., 2007).



Heartrate sensor

Pressure-Sensing Insoles

Pressure-sensing insoles are designed to measure plantar pressure distribution and ground reaction forces (GRFs), which are critical for understanding gait mechanics and managing load during rehabilitation. These insoles, equipped with capacitive and piezoresistive sensors, provide real-time feedback on how the patient's weight is distributed across their feet while walking, running, or standing. Tamm et al. (2014) showed that flexible printed circuit boards (PCBs) integrated with foam cushioning materials could improve the accuracy of pressure readings, making these insoles more suitable for dynamic use. The ability to monitor GRFs is particularly useful for knee rehabilitation, as it helps clinicians assess whether a patient is placing excessive stress on the joint. Despite their advantages, pressure-sensing insoles face challenges in providing reliable data during rapid movements or high-impact activities. Additionally, ensuring patient comfort and sensor durability during long-term wear is essential for successful rehabilitation. Xu et al. (2021) developed a stretchable iontronic pressure sensor capable of accurately predicting knee joint postures.



Pressure insole sensors

Soft and Stretchable Sensors

Soft and stretchable sensors, typically made from conductive fabrics, offer a highly sensitive and comfortable solution for motion tracking. These sensors can detect small movements, such as those associated with knee flexion, with high precision. Gupta et al. (2023) demonstrated knitted sensors capable of detecting motions as small as 0.12°, offering a quick response time of less than 90 milliseconds. These sensors have the advantage of being flexible and lightweight, which reduces discomfort and enhances wearability during long-term use. However, challenges remain in ensuring that these sensors maintain their functionality in various environmental conditions, such as exposure to moisture or sweat. Additionally, ensuring that soft sensors remain durable and washable is essential for their long-term viability in clinical settings.

Temperature Sensors

Temperature sensors measure the local temperature of the skin, which can be an indicator of inflammation or infection, both of which are common concerns during knee rehabilitation. De Marziani et al. (2023) found that elevated skin temperatures around the knee were strongly associated with increased pain in osteoarthritis patients, suggesting that temperature sensors could be valuable tools for monitoring post-surgical recovery. By providing non-invasive, continuous monitoring, these sensors enable clinicians to track the patient's recovery process and make adjustments to the rehabilitation plan when necessary. However, maintaining accurate temperature readings during motion and ensuring that the sensor remains in consistent contact with the skin are major challenges. Advances in flexible and stretchable materials may help address these issues.

Self-Powered Wearables

Self-powered wearables have gained attention due to their ability to harvest energy from the body, eliminating the need for external batteries. These devices typically rely on piezoelectric, triboelectric, or thermoelectric mechanisms to generate power from body movement or heat. For instance, Zhu et al. (2019) demonstrated a self-powered sock designed to monitor health metrics, while Yuan et al. (2023) developed a fully self-powered wearable leg movement sensing system. These technologies offer the potential for long-term monitoring without worrying about battery depletion, making them ideal for continuous rehabilitation tracking. However, challenges remain in generating enough power to support complex functionalities such as real-time data processing or wireless communication. Further developments in energy efficiency and miniaturization are necessary to make self-powered wearables more practical for widespread use.

Bioelectrical Impedance Analysis (BIA)

Bioelectrical impedance analysis (BIA) is a technique used to measure body composition and fluid retention by analysing the resistance of tissues to an electrical current. In knee rehabilitation, BIA can be used to monitor swelling and muscle recovery following surgery. Loyd et al. (2019) demonstrated that BIA could accurately track lower extremity swelling after total knee arthroplasty, providing valuable feedback to clinicians and patients. However, BIA measurements can be affected by movement or changes in body composition, which may reduce the accuracy of the readings. Nonetheless, BIA remains a promising tool for non-invasive monitoring of post-surgical recovery, especially when combined with other wearable sensors.

Ultrasound Sensors and Actuators

Ultrasound technologies are increasingly being integrated into knee rehabilitation wearables for both diagnostic and therapeutic purposes. Ultrasound sensors monitor muscle contractions and joint movements, providing valuable insights into rehabilitation progress. Ultrasound actuators, on the other hand, deliver therapeutic stimulation to soft tissues, promoting healing and reducing pain. Zhang et al. (2015) found that therapeutic ultrasound effectively reduced pain and improved function in knee osteoarthritis patients. Further enhancing the potential for ultrasound in wearable devices. Despite their potential, ultrasound technologies face challenges in miniaturization and integration into compact, wearable forms. Advances in these areas are necessary to make ultrasound-based wearables a practical solution for knee rehabilitation.

VR & AR

Virtual Reality (VR) and Augmented Reality (AR) are useful tools in knee rehabilitation by creating engaging, immersive, or semi-immersive environments that motivate patients and enhance recovery outcomes. Tools like Corpus VR use gamified exercises to immerse patients in virtual settings, helping them stay focused and perform rehabilitation tasks more effectively. These technologies provide real-time feedback, allowing therapists to customize exercises based on individual progress, which can lead to faster and more comprehensive recovery. By making therapy interactive and enjoyable, VR and AR foster patient commitment and offer an innovative approach to physical rehabilitation (Corpus VR, 2024).

Multisensory solutions

Multisensory knee wearables have been experimented with. These devices have shown promising results so has Faisal (2020), in his master's thesis, explored the development of a multisensory wearable platform incorporating inertial measurement units (IMUs), temperature sensors, pressure sensors (measuring muscle pressure), and galvanic skin response (GSR) sensors. This innovative device was designed to track joint motion and gait speed while capturing physiological parameters such as temperature and skin conductance. Utilizing support vector machine learning algorithms, Faisal demonstrated the capability of this wearable to classify knee health data into distinct groups based on demographic and physiological factors, including age, gender, body mass index (BMI), and joint health conditions. The study highlighted the potential of this wearable technology for early detection of joint disorders, mobility monitoring, and rehabilitation purposes, offering a significant advancement in affordable, non-invasive health monitoring solutions.

Teague et al. (2020) adopted a different approach to addressing knee joint health by integrating microphones for joint acoustic monitoring (46.875 kHz) and electrical bioimpedance (EBI) sensors (100–250 Hz) for detecting swelling. These were combined with IMU sensors and temperature sensors in a flexible, 3D-printed brace equipped with microcontrollers and data storage on microSD cards. The system offers notable advantages, including the ability to perform continuous, real-time monitoring for up to 9 hours for acoustics and 35 hours for other sensors, powered by batteries. This ensures extended autonomy make the device suitable for both in-clinic and at-home use. By employing a multimodal approach, the system provides comprehensive insights into joint health, including detecting acoustic signals indicative of joint issues, measuring swelling, and analysing movement patterns. These features represent a significant advancement in early diagnosis and personalized management of knee health.

The SKYRE wearable is designed to improve how we monitor and care for our knees during rehabilitation or athletic training. It uses motion sensors to track how the knee moves, its angles and range of motion, providing detailed insights into joint health. Electromyography (EMG) sensors measure muscle activity around the knee, showing how muscles respond to different activities. On top of that, it includes muscle electro-stimulation, which helps with recovery and strengthening during rehabilitation. (Tedesco et al., 2022)

These multisensory platforms show potential of being used in clinic and at home settings. However, sensor integration for comfort and user-friendliness still needs to be explored. Furthermore, these systems have shown to create multivariable analysis that says a lot but creating actionable data for patients and medical experts still needs to be considered.

Gamification & Imagery

Gamification of rehabilitation exercises and imagery techniques are two promising strategies that combine physical and psychological recovery elements.
Gamification applies game design principles to therapeutic exercises to motivate patients and improve adherence. Key elements of gamified systems include goal-setting, progress tracking, and rewards that transform exercises into engaging tasks. Advanced rehabilitation platforms also integrate sport-specific simulations, biofeedback mechanisms to ensure movement accuracy, and performance thresholds to unlock achievements. These features address the monotony of traditional rehabilitation and actively involve patients in their recovery process.

A notable example of gamification in practice is the Fun-Knee system made in a scientific study. This smart knee sleeve, embedded with sensors, provides real-time biofeedback to help patients accurately perform exercises. Rehabilitation tasks are designed as interactive games, with progress tracking and rewards that sustain motivation. By addressing physical challenges such as improving strength and range of motion and psychological barriers like low motivation, Fun-Knee supports a holistic and enjoyable recovery journey (Qiu et al., 2021). Gamification's ability to create an engaging rehabilitation environment makes it a valuable tool in modern therapeutic approaches.

Imagery techniques, which involve mentally visualizing successful movements and recovery milestones, are a powerful addition to traditional rehabilitation. They help patients overcome fear and anxiety related to reinjury and foster psychological readiness. Research shows that patients who use imagery report significant benefits, including better pain management, greater range of motion, and improved quadriceps muscle activation which is critical for knee stability (Rodriguez et al., 2018). Additionally, imagery reduces stress hormone levels, such as noradrenaline and dopamine, minimizing inflammation and promoting healing.
By addressing the mental and emotional aspects of recovery, imagery techniques complement physical therapy, empowering patients to rebuild confidence in their abilities. This dual focus on mind and body contributes to a more comprehensive and effective rehabilitation process.
Despite their promise, the integration of gamification and imagery techniques in rehabilitation is not without challenges. One significant issue is personalization and difficulty management. Rehabilitation is inherently individualized, and pushing patients too hard with external motivators like games or imagery can lead to overexertion or reinjury. Adaptive systems are necessary to ensure that challenges match patients' current abilities and progress over time.
Another limitation is the focus on micro-level gamification, such as individual exercises, while the overall rehabilitation experience often lacks gamified design. This absence of macro-level gamification may reduce the enjoyment and engagement of the broader process. Additionally, sustaining long-term adherence to rehabilitation protocols remains a challenge, even with innovative tools.
Behavioural science can offer solutions to these challenges, particularly through the application of Yu-Kai Chou's Octalysis Framework for actionable gamification. This framework identifies eight core drives of human motivation:

- Epic Meaning and Calling
- Development and Accomplishment
- Empowerment of Creativity and Feedback
- Ownership and Possession
- Social Influence and Relatedness
- Scarcity and Impatience
- Unpredictability and Curiosity
- Loss and Avoidance

Applying this framework to rehabilitation can create a more habit-forming and enjoyable experience, ensuring sustained engagement and better outcomes. Furthermore, finding what core drivers appeal most to the patient can potentially be used for personalized gamification (Actionable gamification YU KAI CHOU, 2019)

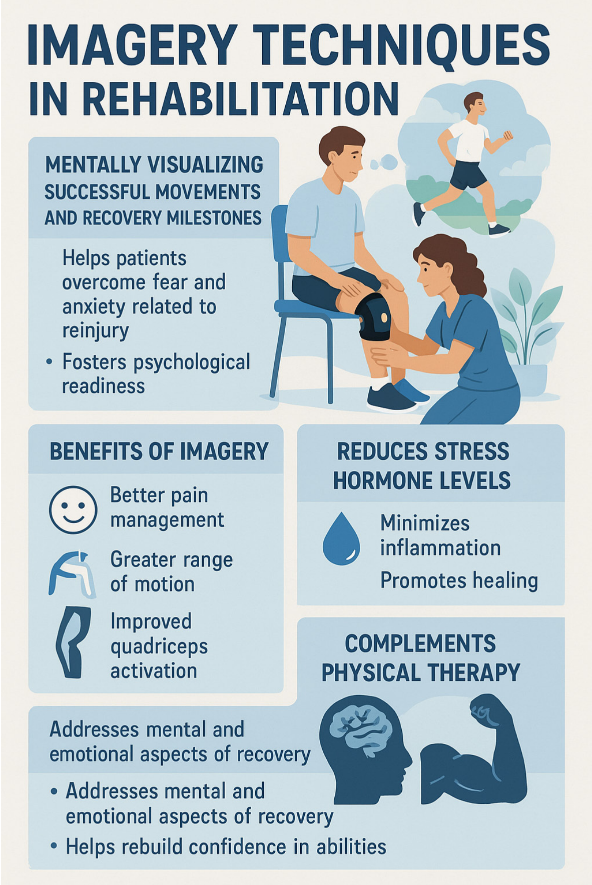


Figure 9: Visualisation of Imagery in knee rehabilitation

1.6. Trends

Analysing technologies, the patient journey, and their associated developments and challenges reveals trends that are helpful for designing effective solutions. This chapter explores and discusses key trends in the economic, technological, and healthcare aspects of knee rehabilitation, giving insights on the factors that are important in physiotherapy future landscape.

One of the big trends is e-health. the financial growth of the e-health sector has been great over the past few years. According to a report (EHealth Market Size, Share & Trends Analysis Report by Product (Telemedicine, Health Information Systems), by End-use (Providers, Payers), by region, and Segment Forecasts, 2024 - 2030, 2024), the global e-health market size was valued at approximately 300 billion dollar in 2023, and it is expected to grow at a compound annual growth rate (CAGR) of 22.5% from 2024 to 2030. This growth is being driven by several factors, including the increasing demand for remote healthcare services, the integration of AI in medical diagnostics, and the growing focus on personalized medicine. The adoption of e-health technologies has similarly expanded across the globe, especially in the wake of the COVID-19 pandemic.
In terms of remote patient monitoring, wearable health technologies are gaining traction as individuals and healthcare providers recognize their potential to enhance patient engagement and reduce hospital readmission rates. The wearable health tech market, which includes devices such as fitness trackers and medical-grade wearables, is expected to grow by more than 25% annually, reaching a market size of 60 billion dollar by 2025 (Rock Health, 2024).
This increase in adoption of wearables and financial growth of the e-health market is showing the need for technologies that assist people monitoring health is desirable in the market especially if cost are rising and medical staff is becoming more scarce.

The integration of technology into daily life is becoming increasingly intimate. The analysis of Technology Readiness Levels (TRL) in knee rehabilitation technologies in section 1.5 reveals a progression from large, external machines used in clinical settings to portable devices, then to wearable technologies, and ultimately to innovations that integrate seamlessly with the human body. This evolution is driven largely by advancements in sensor and actuator technologies, which are becoming smaller, more affordable, and more energy-efficient.
Healthcare is increasingly embracing personalization and the integration of mental and physical well-being. Rehabilitation processes are becoming more tailored to individual needs, recognizing that every person's recovery is influenced by unique factors and goals. Advances in technology play a pivotal role by enabling precise measurement of physiological adaptations, which are essential for creating personalized treatment plans. Simultaneously, the growing awareness of psychological health highlights the profound impact of emotions, stress, and illness beliefs on physical recovery. Factors such as fear and stress can affect coordination, blood pressure, and heart rate, underscoring the necessity of addressing psychological and emotional barriers. By integrating mental and physical rehabilitation, healthcare can deliver more comprehensive and effective treatments, enhancing overall patient outcomes.

1.7. Competitor analysis

The competitor analysis was done to identify what already is on the market regarding physiotherapy, physiological and mental tracking. In figure 10 are identified competitors. The size of the logo was decided based on a few factors:

- **How specific the company focuses on physiotherapy**
- **Specification on knee rehabilitation**
- **Company size and impact**
- **Technologies used**

Analysing the competitors in the market shows that the need for technological innovation is prevalent. These competitors each have different strategies. Many focus on clinical activities and digitalizing them, such as measuring home exercise routines and creating platforms for telerehabilitation. Some provide physiotherapists with information enhanced by machine learning and AI algorithms. Others go a step further by incorporating gamification to mitigate pain during rehabilitation and make exercise routines more engaging. Examples of such competitors include Eularia, Swordhealth, and CorpusVR. Other competitors concentrate on sports performance and improving metrics. For example, RunScribe and Moticon offer solutions to enhance the gait patterns of runners. A unique approach to sports enhancement is taken by Whoop, which focuses on measuring recovery for professional athletes. Similarly, Garmin and Polar emphasize providing customers with biometric data to help them adapt their lifestyles for optimal performance.
Kinexcs specializes in knee rehabilitation with a focus on long term tracking. Their emphasis on measuring metrics such as stair walking and other daily activities makes them stand out in the market. Moreover, their use of a patented stretch sensor strengthens their position. Unlike many competitors, Kinexcs adopts a macro perspective on recovery rather than focusing solely on individual exercise sessions.

Figure 10: Competitor analysis

1.8. Scope

The objective of this project is to develop a wearable device capable of producing actionable data to support engaging and effective knee rehabilitation. Interviews with patients revealed that the final stages of rehabilitation present significant challenges. Fear of re-injury or loss of mobility often dominates this period, negativly effecting progress. Therefore, this project focuses on facilitating physical rehabilitation while prioritizing the prevention of re-injury (see Figure 10).
One key challenge identified during knee rehabilitation is the misalignment between mental and physical recovery. This phenomenon, known as parallel recovery, highlights the need for integrated solutions that address both aspects simultaneously. The wearable device developed in this project will aim to facilitate parallel recovery by bridging the mental and physical dimensions through technological support.

Technical Scope

The focus of this project is on a wearable solution, deliberately excluding technologies such as camera tracking, virtual reality (VR), and augmented reality (AR) from its scope. Wearables provide several advantages, including the ability to perform continuous measurements during daily activities and adaptability to different environments, such as sports settings. Additionally, wearable devices can collect skin-contact metrics, which are beyond the capability of camera-based systems. While AR or VR integration could enhance the solution in the future, they are intentionally omitted from this phase of development.

Potential Challenges and Unintended Side Effects:

- Overdependence on the Device

There is a risk that users may become overly reliant on the wearable. To mitigate this, the device should be designed to gradually reduce external inputs, fostering the development of independent management strategies through habit formation.

- Overwhelming or Non-Actionable Data

Providing excessive or irrelevant data can lead to anxiety, stress, or overthinking. It is essential that the device prioritizes actionable metrics and distinguishes between information displayed to the patient and data accessible to the physiotherapist. This separation allows the physiotherapist to interpret detailed insights and recommend appropriate interventions without overburdening the patient.

- Privacy and Data Security

The wearable will collect sensitive medical data, necessitating robust safeguards against unauthorized access or data breaches to ensure patient privacy and compliance with medical data protection standards.

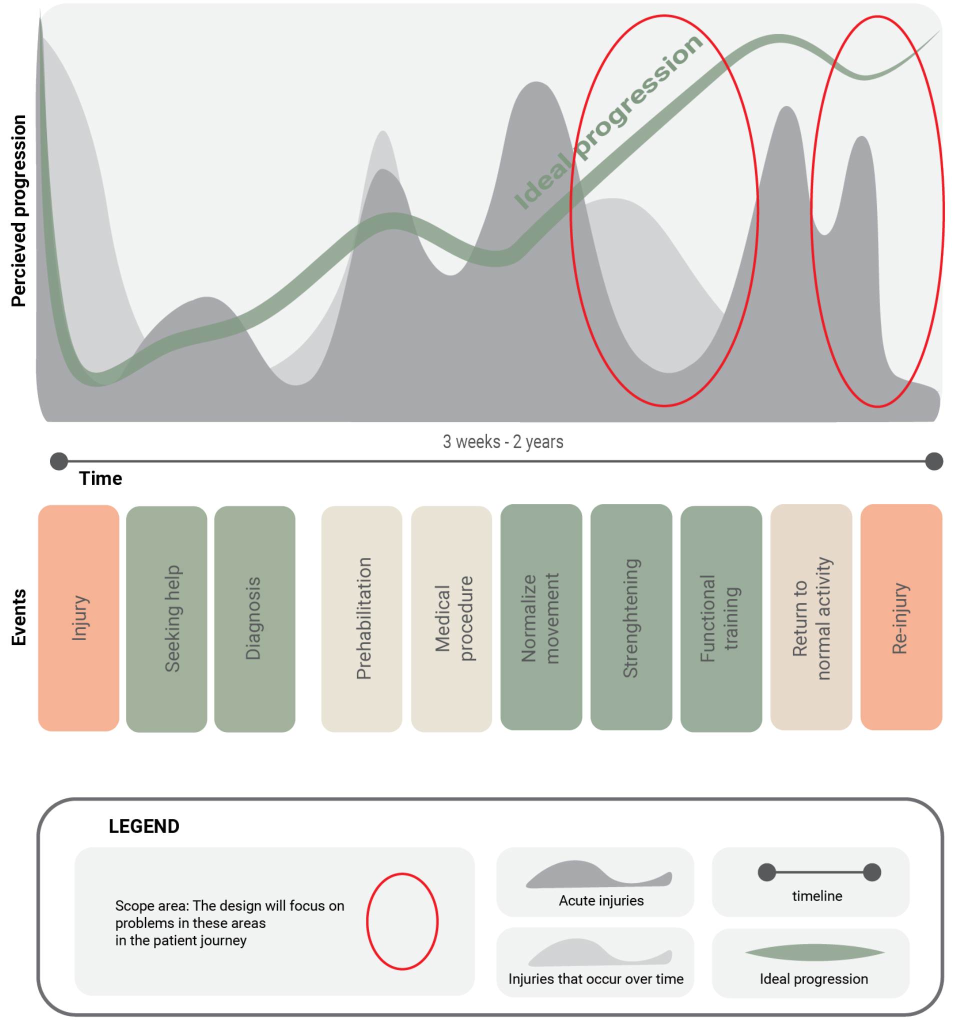


Figure 10: Patient journey with scope indicator

1.9. Criteria

Having established a defined scope to start the Ideation phase (Chapter 2), a list of criteria was developed to guide the design process. The criteria were formulated to ensure that the ideation process remains aligned with the project scope.
The criteria were designed to evaluate and compare the generated ideas systematically, facilitating the selection of a final concept that optimally balances innovation, feasibility, and alignment with the project's goals.
The criteria will be used in the concept selection of this project.
The criteria can be found in Figure 11. Each criteria has been given a weight factor, highlighting the importance of that factor in the design process. Looking at the criteria, this shows a higher importance placed on the impact on the patient and user experience compared to factors like technical function and cost in this project.

Design Criteria	weight	score (1-10)	total
patient-cantered impact	**total: 30**		
patient impact	12		
therapeutic value	10		
patient depence risk	3		
Personalisation	3		
inclusiveness	2		
User Experience	**total:23**		
Ease of Use/Setup	5		
Comfort	5		
Correct Sensor Placement	4		
Adjustability (Ergonomics)	3		
Hygiene	3		
Portability	2		
Aesthetic Appeal	1		
Data and Interface Usability	**total:20**		
Actionable Data	10		
Intuitive Interface	7		
Data Security & Privacy	3		
Technical and Functional Performance	**total:15**		
Accuracy of Data	5		
Latency of the System	3		
Energy Consumption	3		
Durability	2		
Water Resistance	2		
Affordability and Market Viability	**total:10**		
Affordability	5		
Adoption	3		
Market Differentiation	2		
Sustainability and Lifecycle	**total:2**		
LCA (estimate)	2		
Total	100		0

Figure 11: Criteria

2. Ideation

In this chapter the scope of solution space is explored with ideas and crafted into concepts. During ideation, physical and mental aspects where combined using technical tools like sensors and actuators to quickly find combination of ideas resulting in three main design directions. After that concept(s) were created and evaluated resulting in a final concept that will be prototyped and detailed further in the project.

2.1. Idea & concept creation

With a focus on parallel recovery and the later stages of the patient journey, the ideation process began with brainstorming and sketching wearable concepts without significant judgment. Appendix I, L includes the brainstorming sessions and initial sketches. Over time, this process became more structured, culminating in the creation of a systematic framework referred to as the "Idea Factory" for this project (see Figure 12).

The ideation process combined three key elements: physical aspects, mental aspects, and tools. These elements guided the categorization of ideas into two primary groups: continuous measurement and activity monitoring, such as sports or physical therapy sessions.
By utilizing the Idea Factory, three major themes or design directions emerged:

1. Holistic measures
2. Load management
3. Minimalistic modernization

These design directions are explained on the next page. For each direction a idea was selected. This idea was turned into a concept direction for detailed evaluation. The descriptions of these concepts are explained after the design directions in this report (page 47).

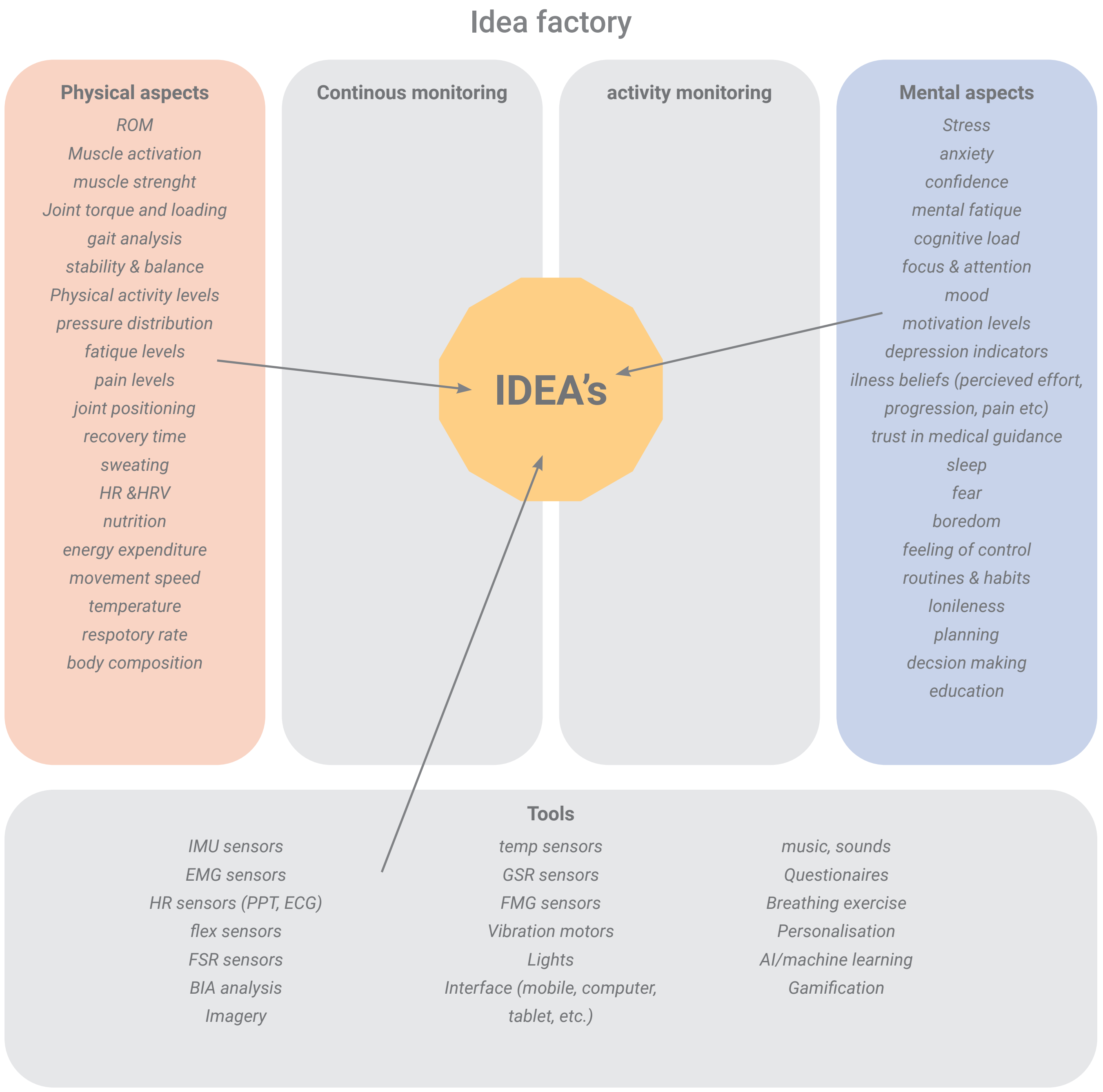
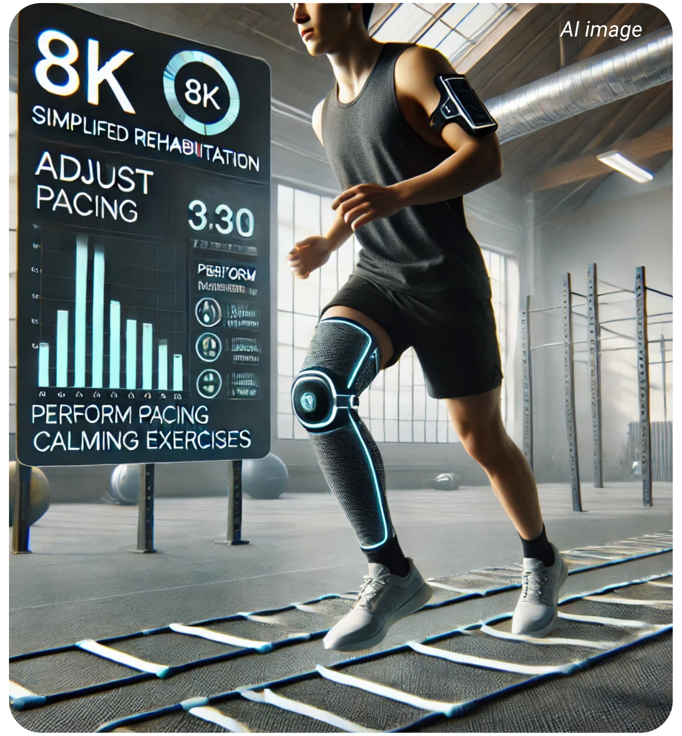


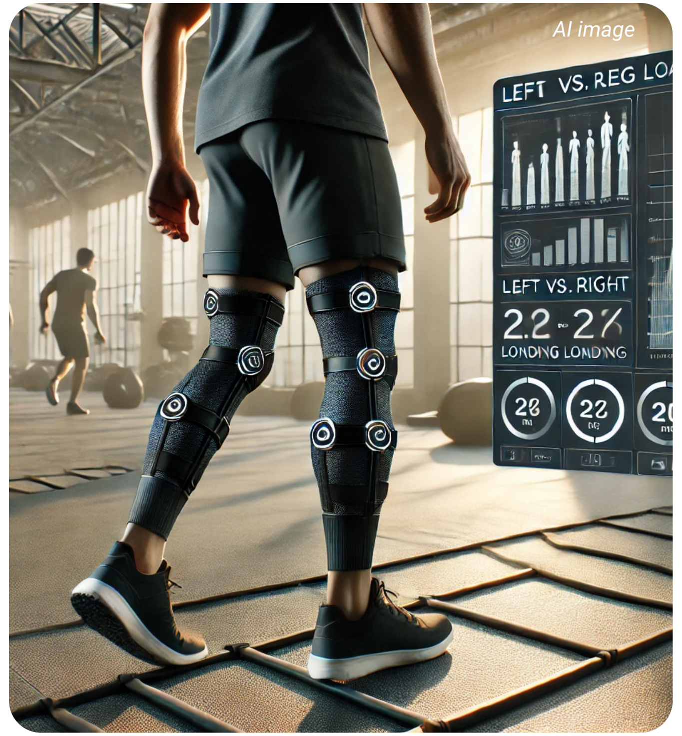
Figure 12: Idea factory for parallel recovery solutions



1. Holistic measures

This approach integrates physiological emotional signals and biomechanical data to provide insights for patients during knee rehabilitation. Key features include:

- **Linking Emotions to Movement:** Identifying emotional triggers associated with specific movements.
- **Belief-Data Comparison:** Aligning patient beliefs about their illness with measurable data for better understanding.
- **Personalized Exercises:** Generating actionable physical and mental exercises based on the collected data, delivered through an interactive interface.
- **Pain and/or Stress Monitoring:** Detecting and analysing levels of pain and stress for targeted interventions.



2. Load management

This approach provides in-depth insights and feedback on proper knee loading by analysing detailed knee biomechanics and aligning them with patient illness beliefs. Key features include:

- **Belief-Data Integration:** Comparing detailed movement data with patient perceptions of their condition.
- **Muscle Activation Monitoring:** Tracking patterns of muscle activation during movement.
- **Muscle Fatigue Analysis:** Identifying signs of muscle fatigue for optimal recovery.
- **Improper Loading Alerts:** Detecting and addressing improper knee loading through reaction force analysis.
- **Ground Reaction Force Measurement:** Evaluating how forces impact the knee.
- **Leg Comparison Analytics:** Comparing data between legs to identify imbalances and asymmetries

3. Minimalistic modernization

This approach emphasizes streamlining the rehabilitation process by focusing on a user-friendly digital interface while reducing the need for extensive hardware. Key features include:

- **Illness Belief and Emotional Tracking:** Utilizing questionnaires to gather insights on patient perceptions and emotional states.
- **Motivation and Adherence Support:** Providing tools to encourage consistent participation and engagement in rehabilitation.
- **Gamified Measurements:** Modernizing traditional assessment tools with interactive and gamified elements to enhance the user experience.

This direction aims to simplify rehabilitation while maintaining effectiveness and user engagement.

1. Symphysis (concept)

Brings physical and mental together in knee rehabilitation using a technical approach

This wearable concept integrates three sensor systems: Inertial Measurement Units (IMU's), a Galvanic Skin Response (GSR) sensor, and a Photoplethysmography (PPG) sensor to provide comprehensive insights into both biomechanical and physiological states during knee rehabilitation.
The IMU is employed to measure key biomechanical metrics such as knee joint angles and jerk over time, offering precise data on the patient's movement patterns and rehabilitation progress. Complementing this, the GSR and PPG sensors capture physiological parameters, including heart rate (HR), heart rate variability (HRV), blood oxygen saturation (SpO2), and skin conductance. These metrics are well-established indicators of stress and emotional arousal, providing valuable insights into the patient's physiological responses during exercise, and daily activities.
By combining these datasets, the system detects correlations between emotional and physical responses. For example, increased heart rate, reduced HRV, and elevated skin conductance, potential markers of stress, are analysed alongside biomechanical data such as movement speed and joint stability. This integration allows for the identification of stress-induced disruptions in movement quality, offering a novel perspective on the interplay between psychological and physical states during rehabilitation.
The system's interface provides actionable insights to the patient, such as tailored exercises or relaxation techniques to mitigate stress-induced triggers. Additionally, data can be compared with self-reported questionnaires addressing illness beliefs and mental health in an interface (app or desktop). This approach equips physiotherapists with a holistic understanding of both mental and physical barriers to recovery, facilitating personalized and effective treatment plans.

This multi-sensor, data-driven methodology not only enhances the precision of rehabilitation monitoring of mental and physical health in recovery outcomes. It represents a forward-thinking approach to knee rehabilitation that integrates cutting-edge technology with a patient-centred focus.

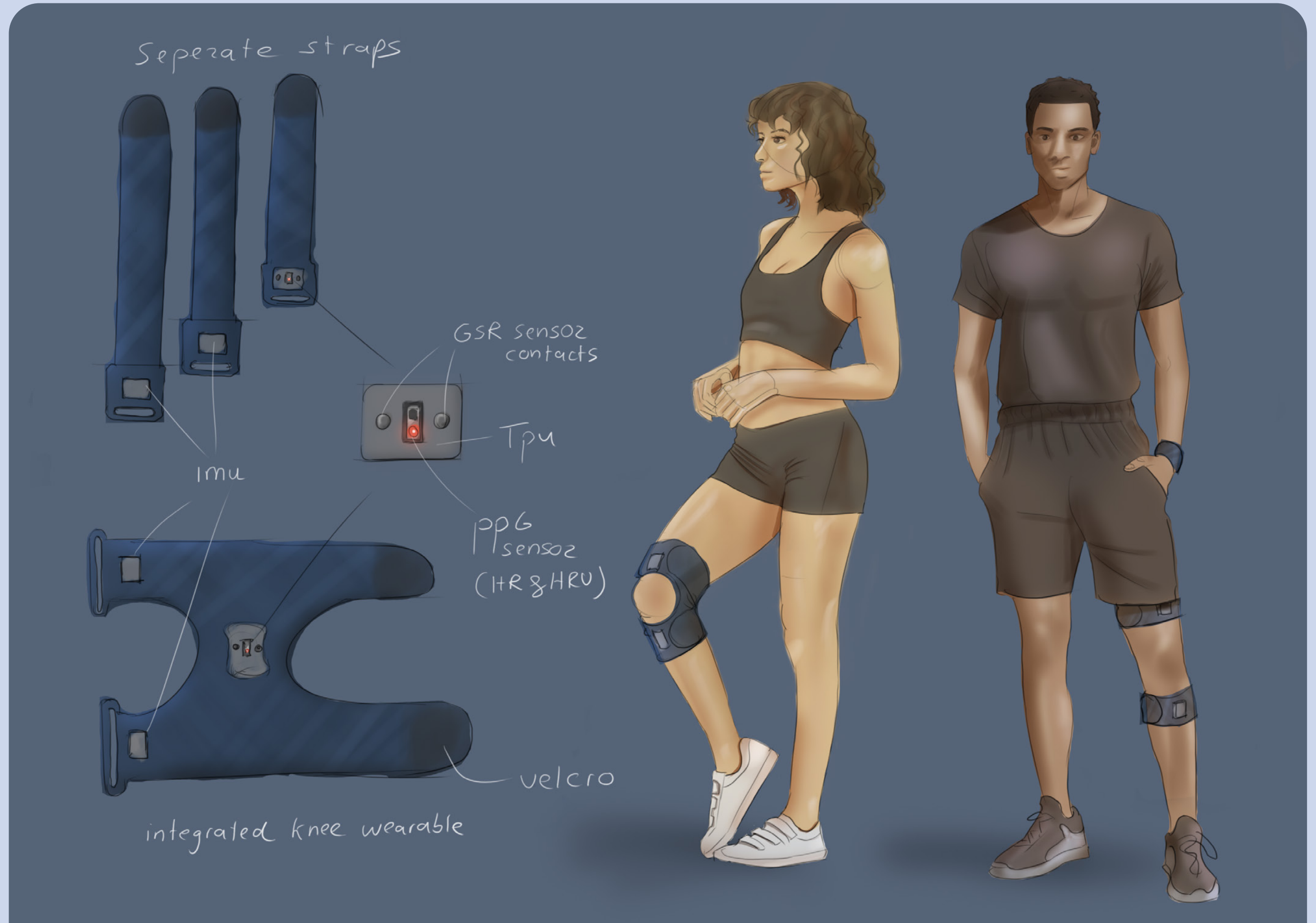


Figure 13: Symphysis concept direction wearable sketch

Benefits for Patients:

- Gain a better understanding of the connection between emotions and movement.
- Receive personalized exercises for both physical and mental challenges.
- Feel more engaged in your recovery with clear, visual insights.

Benefits for Physiotherapists:

- Understand mental and physical barriers that impact recovery.
- Use data to guide conversations and provide targeted support.
- Create a treatment plan that aligns mental and physical recovery.
- Gain insights into movement patterns, including range of motion, speed and acceleration.

2. PairityMotion (concept)

Balanced knee rehabilitation by identifying assymetries

These wearable system ideas combine biomechanical sensors, including Inertial Measurement Units (IMUs), Electromyography (EMG), and Force Sensing Resistors (FSRs), to analyze muscle activation, joint biomechanics, and force distribution. It goes beyond basic metrics like knee angles and movement speed to deliver detailed insights into muscle engagement and loading dynamics during rehabilitation.
The dual knee sleeve design allows for comparative analysis between injured and uninjured knees, identifying discrepancies in movement and loading patterns. This symmetry-focused feedback helps patients achieve balanced joint mechanics. Real-time guidance ensures proper exercise form, reducing compensatory movements that could hinder recovery or cause further injury.
A complementary long-sleeve sock with force sensors captures precise ground reaction force (GRF) data during weight-bearing activities. Timely warnings are issued to prevent harmful overloading, enabling patients to adjust movements or intensity.
The system integrates self-reported data on illness beliefs and injury perceptions through an interactive interface, aligning mental understanding with objective metrics. This holistic approach enhances rehabilitation compliance, fosters confidence, and bridges the gap between mental and physical recovery.

By delivering high-resolution feedback and facilitating load management, these wearable systems provide an innovative solution for safe and effective knee rehabilitation. It empowers patients and clinicians with the tools to optimize recovery, prevent injury recurrence, and restore functional symmetry.

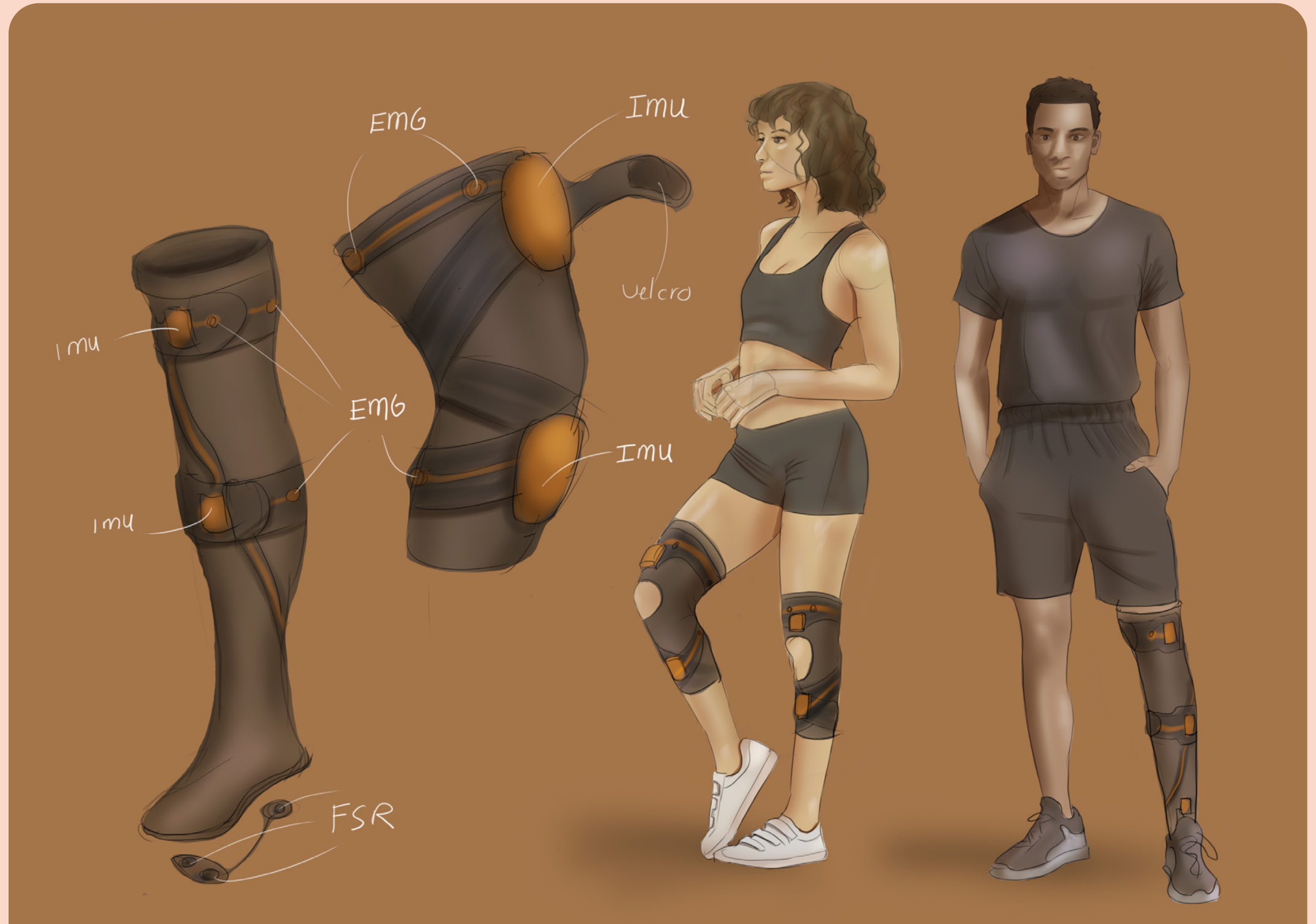


Figure 14: PairityMotion concept direction wearable sketch

Benefits for Patients:

- Understand your knee recovery through clear visual comparisons with your healthy leg.
- Achieve a safe recovery with personalized feedback and exercises.

Benefits for Physiotherapists:

- Identify imbalances and asymmetries.
- Use objective data to support expertise and enhance guidance.
- Monitor muscle activation, range of motion, gait patterns, and patient perspective for a complete recovery picture.

3. Movesphere (concept)

Brings physical and mental together in knee rehabilitation using a technical approach

This approach emphasizes affordability, simplicity, and user engagement by utilizing a streamlined hardware setup consisting of just two Inertial Measurement Units (IMUs). These sensors provide essential biomechanical data, such as knee joint angles and movement speed, ensuring accurate and reliable tracking of rehabilitation progress without the complexity or cost of more extensive sensor arrays.
The system's interface reimagines traditional assessment methods by integrating gamified, interactive tools that engage patients in exploring their emotional state and illness beliefs. By transforming conventional questionnaires into an engaging game experience, the system encourages active participation and ensures consistent patient input. This self reported data is dynamically combined with biomechanical insights to promote parallel recovery of physical function and mental well-being.
The minimalist design keeps hardware costs low and prioritizes ease of use, making the wearable accessible to a broader range of patients. While the system relies on greater patient interaction, it leverages this need as an opportunity to foster a sense of ownership in the rehabilitation process. Thoughtfully designed engagement mechanisms, such as rewards for consistent participation and progress milestones, maintain high adherence rates and improve outcomes.

This modernized approach delivers significant value by addressing both the mental and physical dimensions of recovery without requiring expensive or complex setups. By focusing on simplicity, affordability, and patient engagement, this wearable technology offers an innovative and accessible solution for effective knee rehabilitation.

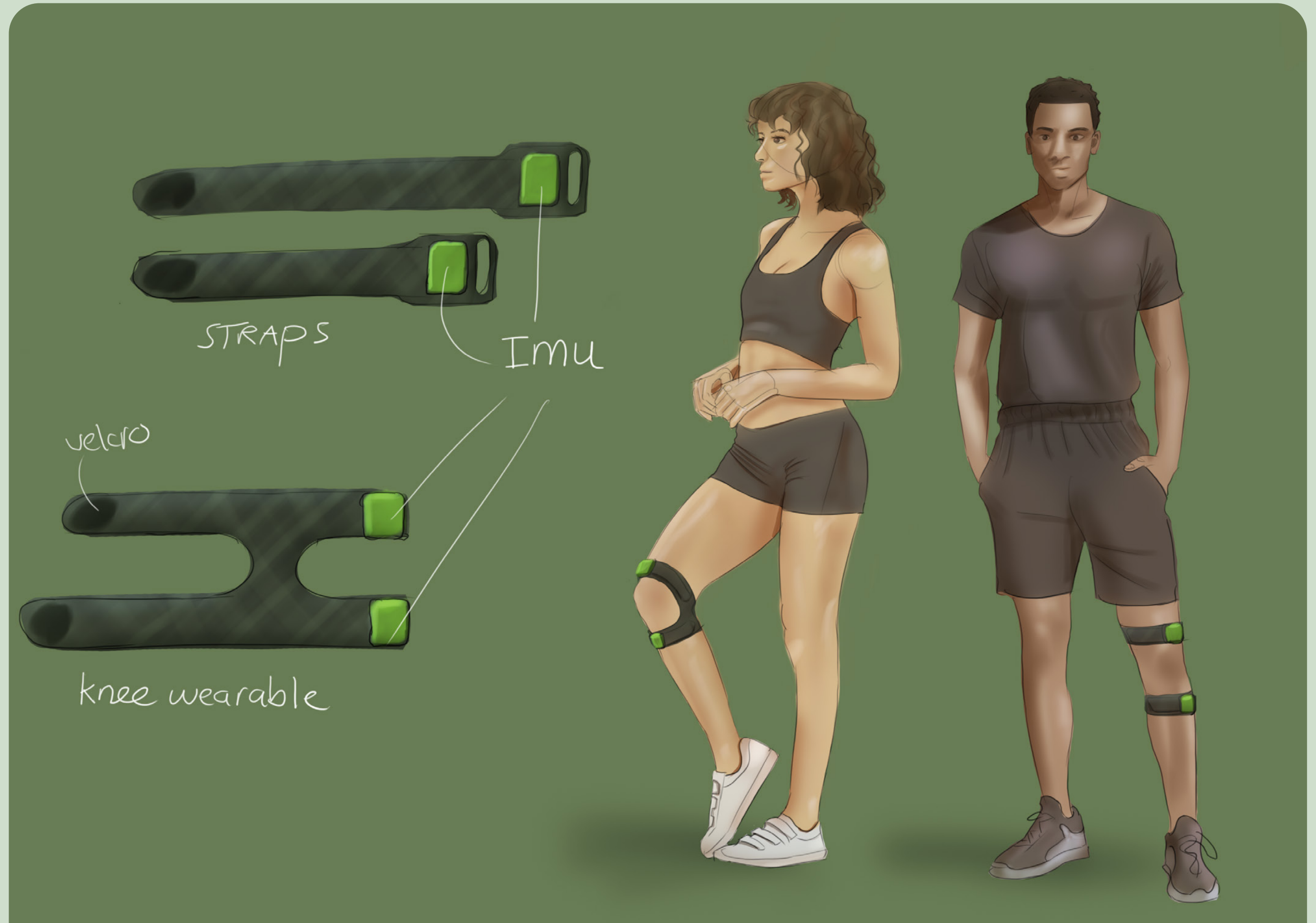


Figure 15: Movesphere concept direction wearable sketch

Benefits for Patients:

- Stay motivated with a gamified recovery process.
- Gain clear feedback on your movements and progress.
- Discover the connection between beliefs and physical performance through an intuitive interface.

Benefits for Physiotherapists:

- Access a clear overview of patient progress.
- Understand how mental factors, such as beliefs, impact recovery.
- Use a system that encourages consistent engagement and collects valuable data.

2.2. LOW-FI Prototyping

Before evaluation of the three concepts can be done, exploration of technical principles and integration has been tested. The goals of this first prototyping stage are to discover challenges with sensor integration and evaluation of simple to use straps for streamlined user interaction. The benefit of knowing the challenges these elements bring in the design process can help to make decisions on technical feasibility and user friendliness.

The prototypes included paper models, fabric-integrated knee sleeves, and breadboard electrical prototypes for sensor testing.

Paper prototypes were used to assess functional strapping, fabric interconnections, and figure out logical strap placements and user interaction to thighten them.

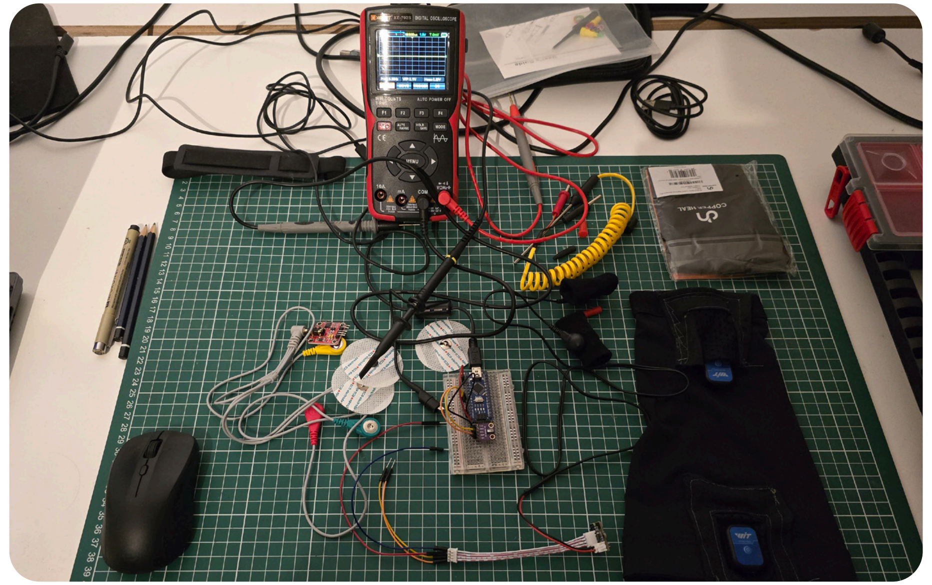
For fabric integration, a knee sleeve was modified with thigh and shin pockets housing two 9-axis IMUs to measure knee angles in real time. However, the sleeve struggled with accuratly detecting internal and external rotation due to sensor slippage. Proper tension in the pockets was needed, suggesting individual straps might be more effective.

Breadboard prototypes tested a GSR sensor for skin conductance, a GY-MAX30102 PPG sensor for heart rate measurements, and an EMG sensor for VMO (one of the quadriceps muscles) activation. An oscilloscope helped visualising sensor behaviour and refine signal quality before developing test codes. Reliable readings from the GSR and PPG sensor required firm skin contact. When integrating this in the wearable design this need to be taken into account. While EMG sensors also requires Fixed contact, it also needed precise placement, highlighting the need for adjustability or personalization in wearable integration.

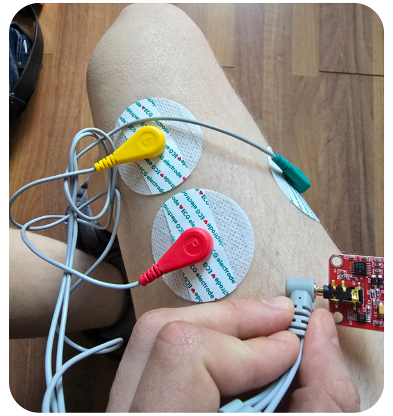
Knee sleeve prototype

pocket on the knee sleeve

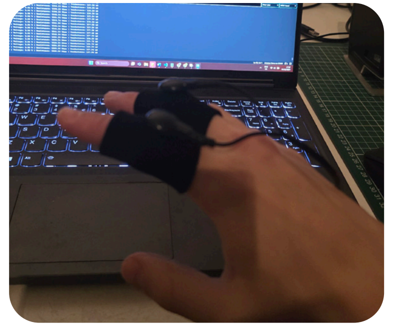
Sensor placement in pocket



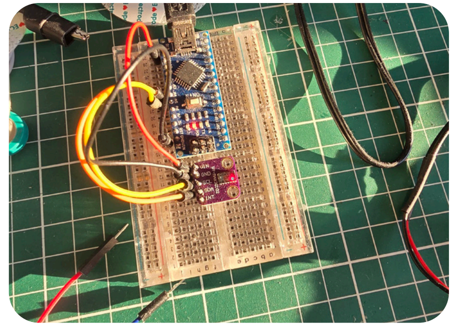
Overview electronic prototype material



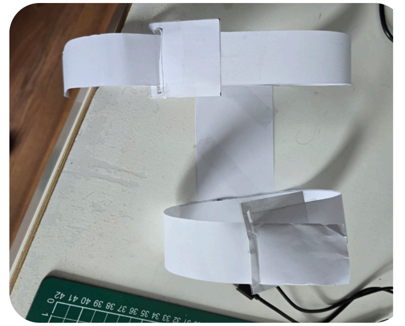
EMG on VMO



GSR sensor



PPG sensor on breadboard



Paper prototype

2.3. Concept Evaluation

The choice of the concept for further development was chosen using the weighted criteria method and brochure testing. In this section the concept choice is explained.

The Criteria framework formulated in 1.9. was used to grade the concept. The grades where given on a 0 - 10 scale and multiplied by the importance factor (weight). these scores where added up to come to a result see figure 16.

These results indicated that the concept ParityMotion scored low compared to the other two concepts. The concept failed on user expericee especially in ease of use and easy sensor placement criteria's.
The other two concepts, Symphysis and Movesphere, scored identical but have different unique selling points and focus area's. Movesphere has a slight advantage on user experience, While Symphysis has a more potential in Patient impact and Novelty.
In order to decide between these concepts an aditional small analysis was performed. For each of the three concepts a brochure was made (in Dutch), see appendix M. These brochures where used in a discussion with a former physiotherapist and other students.
The ParityMotion was confirmed not be ideal for this case.

The concept focusses on leg comparison and detailed mesurements however there will always be assymetries in the body and sometimes an additional injury could also hinder the other leg making comparing not usefull.
Movesphere was something the physiotherapist saw potental in, but had concerns about the many interaction a patient might need to do. Making it fun and simple to interact with is key to the succes of this concept.
Symphysis sparked the curiosity of people, but also raised questions like how would it work? it it reliable? and how to convey this message to a patient or medical professional?

Therefore, the Symphysis concept was chosen. It raised many technical questions and has the potential to be more novel in the aproach to knee rehabiltation.

Symphysis	weight	score (1-10)	total
patient-centered impact	**total: 30**		**223**
patient impact	12	8	96
therapeutic value	10	7	70
patient depence risk	3	4	12
Personalisation	3	9	27
inclusiveness	2	9	18
User Experience	**total:23**		**163**
Ease of Use/Setup	5	8	40
Comfort	5	7	35
Correct Sensor Placement	4	6	24
Adjustability (Ergonomics)	3	8	24
Hygiene	3	8	24
Portability	2	8	16
Aesthetic Appeal	1	0	0
Data and Interface Usability	**total:20**		**144**
Actionable Data	10	8	80
Intuitive Interface	7	7	49
Data Security & Privacy	3	5	15
Technical and Functional Performance	**total:15**		**84**
Accuracy of Data	5	3	15
Latency of the System	3	7	21
Energy Consumption	3	8	24
Durability	2	6	12
Water Resistance	2	6	12
Affordability and Market Viability	**total:10**		**79**
Affordability	5	8	40
Adoption	3	7	21
Market Differentiation	2	9	18
Sustainability and Lifecycle	**total:2**		
LCA (estimate)	2	8	16
Total	100		709

ParityMotion	weight	score (1-10)	total
patient-centered impact	**total: 30**		**226**
patient impact	12	8	96
therapeutic value	10	8	80
patient depence risk	3	3	9
Personalisation	3	9	27
inclusiveness	2	7	14
User Experience	**total:23**		**109**
Ease of Use/Setup	5	5	25
Comfort	5	6	30
Correct Sensor Placement	4	4	16
Adjustability (Ergonomics)	3	2	6
Hygiene	3	6	18
Portability	2	7	14
Aesthetic Appeal	1	0	0
Data and Interface Usability	**total:20**		**160**
Actionable Data	10	9	90
Intuitive Interface	7	7	49
Data Security & Privacy	3	7	21
Technical and Functional Performance	**total:15**		**95**
Accuracy of Data	5	8	40
Latency of the System	3	6	18
Energy Consumption	3	5	15
Durability	2	6	12
Water Resistance	2	5	10
Affordability and Market Viability	**total:10**		**64**
Affordability	5	5	25
Adoption	3	9	27
Market Differentiation	2	6	12
Sustainability and Lifecycle	**total:2**		
LCA (estimate)	2	5	10
Total	100		664

Movesphere	weight	score (1-10)	total
patient-centered impact	**total: 30**		**189**
patient impact	12	6	72
therapeutic value	10	6	60
patient depence risk	3	6	18
Personalisation	3	7	21
inclusiveness	2	9	18
User Experience	**total:23**		**179**
Ease of Use/Setup	5	8	40
Comfort	5	8	40
Correct Sensor Placement	4	8	32
Adjustability (Ergonomics)	3	9	27
Hygiene	3	8	24
Portability	2	8	16
Aesthetic Appeal	1	0	0
Data and Interface Usability	**total:20**		**144**
Actionable Data	10	6	60
Intuitive Interface	7	9	63
Data Security & Privacy	3	7	21
Technical and Functional Performance	**total:15**		**106**
Accuracy of Data	5	5	25
Latency of the System	3	8	24
Energy Consumption	3	9	27
Durability	2	9	18
Water Resistance	2	6	12
Affordability and Market Viability	**total:10**		**73**
Affordability	5	9	45
Adoption	3	8	24
Market Differentiation	2	2	4
Sustainability and Lifecycle	**total:2**		
LCA (estimate)	2	9	18
Total	100		709

Figure 16: Weighted criteira method for the three concepts

3. Product

In the previous chapter was explained how ideas for the parallel recovery assistance product took shape and how the concept "Symphysis" was chosen for further development. In this Chapter the Final product concept is presented in a short product description. Aditionally the design of the Symphysis kit is explained. Futhermore the symphysis system is explained and how it would be integrated in knee rehabilitation with some future step ups for the UI/UX development. After that manufacturing, cost and market viability will be presented. Lastly, a validation plan of this concept is presented.

3.1. Product introduction

Symphysis is a wearable system designed to seamlessly integrate physiological and biomechanical insights into the knee rehabilitation process. By tracking physiological responses to emotions and biomechanical data, Symphysis opens a new dimension to recovery by providing a tool for parallel recovery in knee rehabilitation, one where emotional response to movement is as measurable and actionable as physical progress. This system empowers both patients and healthcare professionals to identify and overcome psychological barriers, such as movement anxiety, bad illness beliefs and pain anticipation, facilitating a more holistic and effective rehabilitation journey.

Symphysis focusses on advanced actionable feedback for patients and professionals while maintaining a user-friendly approach. The wearable system is designed such that it can be used without prior medical knowledge making it ideal for everyday use by patients. The wearable system consists of three modules placed on the key anatomical points on the body using adjustable straps allowing for a universal design that can be comfortably used by 90% of the population. The modules are lightweight and placed on the wrist, thigh and shin, see figure 17. The modules of the Symphysis system are interconnected with the Symphysis application. The application provides possibilities for telerehabilitation, real time & remote monitoring, interactive questionnaires for illness beliefs and actionable data to deal with emotional discomfort by providing cognitive exercises to bring down physiological stress indicators like a low HRV or high skin conductance to optimize emotional resilience alongside physical strength.

One of the benefits of Symphysis is emotion aware rehabilitation. Symphysis detects physiological responses to emotional arousal and stress, including heart rate variability (HRV), the galvanic skin response and real time motion tracking, to identify moments of discomfort during movement.
In combination with traditional measurement instruments like scale questionnaires for fear, pain, cognitive beliefs and assessment of own abilities (illness beliefs) the symphysis system opens the conversation about these combined with actual data measuring the effect of cognitive exercise like imagery, a patient envisions a good outcome, or breathing exercises during or before fearful movements.

Symphysis

Facilitating parallel recovery

Symphysis is a lightweight, wearable solution that tracks both physical and emotional responses during rehabilitation. With 12-hour continuous monitoring and an intuitive, gamified telerehabilitation experience, it helps balance load VS capacity for optimal knee recovery. Its smart feedback loop ensures a holistic, personalized approach to rehabilitation.

Figure 16: Symphysis

3.2. The Symphysis wearable sensorkit

As explained in the product description the Symphysis system makes use of three modules to detect physiological responses related to movement. In this section the sensorkit worn by the patient is explained and how this sensorkit is used.

The sensor kit consists of the parts presented in figure 18, it contains the three modules, each with a strap to wear it on the body. Furthermore, the kit contains a charging block and a bag for easy transport. For requirements for this sensorkit see appendix N.

Setup procedure sensor kit

Using the symphysis wearable kit is straightforward. The patient charges the modules using the provided powerbrick by connecting the USB-C cables to the modules. When the sensorkit is charged it can perform continous monitoring for 12 hours.
The user shortly presses the powerbuttons on each module, allowing the devices to connect to a smarthphone using Bluetooth Low Energy (BLE) with a range over 50 meters.
The user wears the wristmodule on the skin using the adjustable strap ensuring proper skin contact.
The thigh and shin module are placed inside the strap pocket and strapped to the body by placing the sensorpockets on the front of the leg, wrapping the strap around the leg, pulling the strap through the plastic guide on the other side of the pocket, pull it tight and securing it using the velcro on the end of the strap. These straps can be placed underneath clothing or above.
After that the user can open the Symphysis App and start recording. Before recording can be started a calibration pose is asked from the user, to calibrate the movement sensors in the thigh and shin module. After calibration is complete the system is ready to use. see user scenario on page 55.

Comfort and realibility

To esure the modules are comfortable to wear the modules are designed to be lightweight and where no skin contact is needed by the modules, comfortable fabrics are used to minimize iritation. The lightweight of the modules makes the sensor less vulnerable for relative movement in orientation of the skin. this allows for optimal sensor readings without too much movement of the sensor itself.
The wristmodule weight is arround 12 grams while the shin and thigh module weight arround 10 grams, without straps.

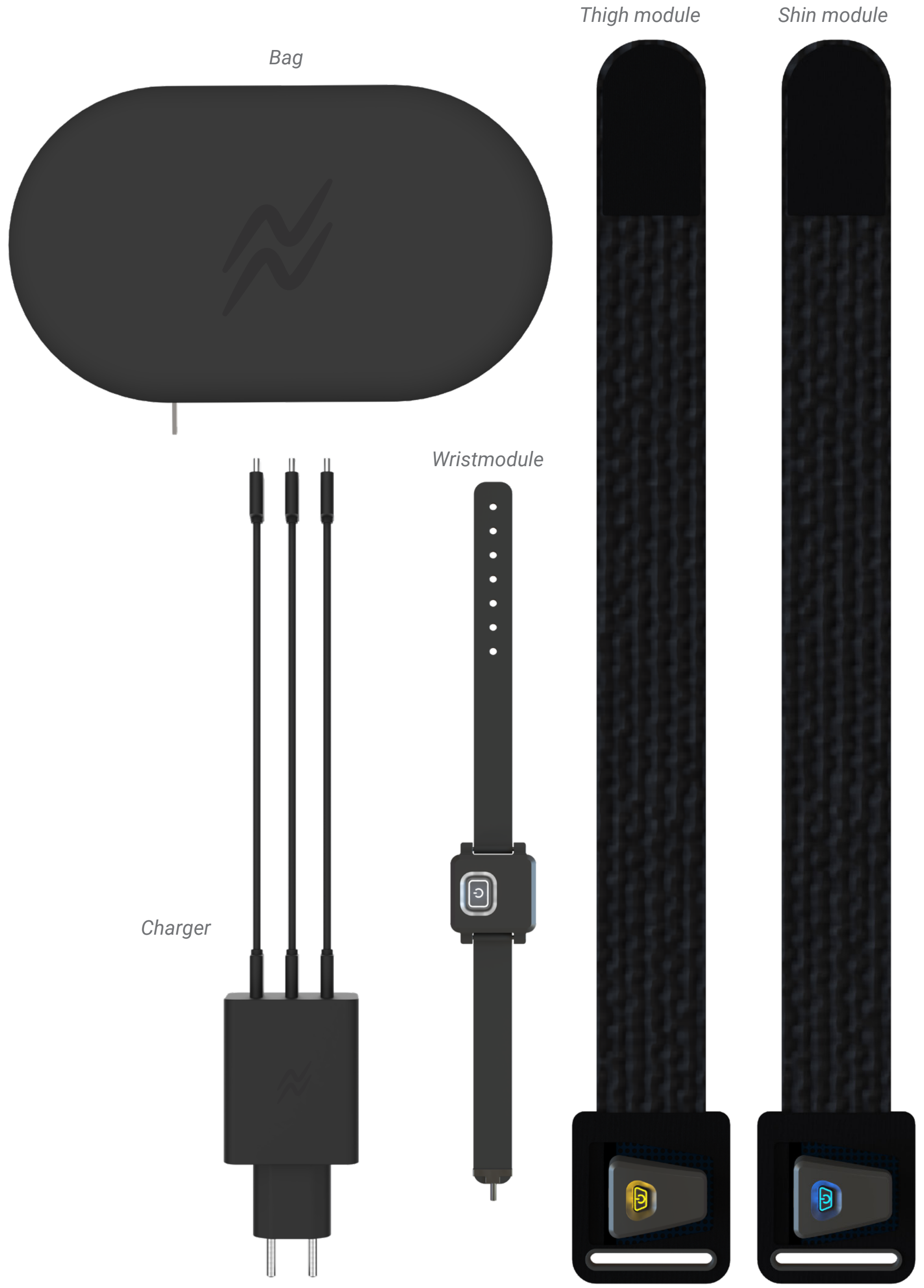
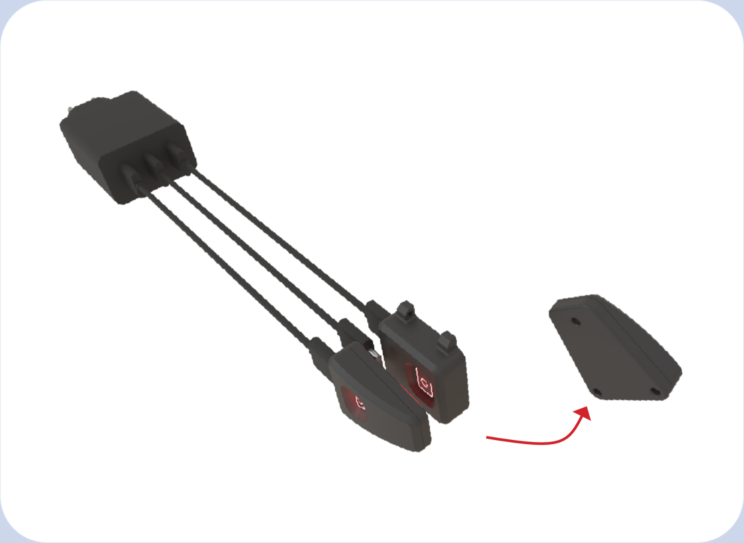


Figure 18: Symphysis sensorkit

Setting up the sensorkit

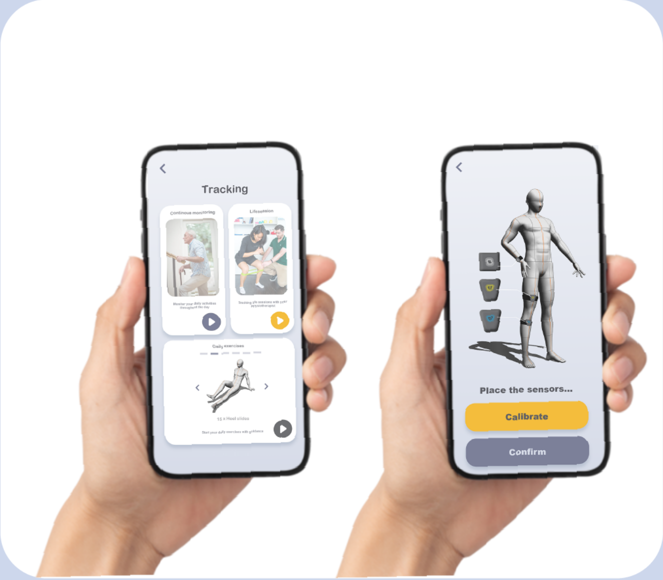


Step 1: Taking the modules from the charger

Step 2: Pressing the buttons on the modules to couple the sensors to your phone

Step 3: assemble the modules to the straps

Step 4: Strap the system on the body



Step 5: choose your tracking purpose and calibrate the movement sensors

Step 6: track your daily activities, rehabilitation sessions and perform your daily gamified exercises

3.3. The Symphysis system

The Symphysis sensorkit provides the data where the symphysis system can provide the new perspective in knee rehabilitation. as explained in section 1.8., this design focuses on the physical rehabilitation of the process, starting at normalizing movement to functional training and providing feedback in the difficult process of getting back to normal activities like competitive sport or maintenaince exercises, while preventing re-injury.
This section explores the integration of the Symphysis system in knee rehabilitation, highlighting how it empowers both patients and healthcare professionals to achieve optimal recovery outcomes.

Symphysis in knee rehabilitation

The Symphysis system starts with the purchase of the Symphysis rehabilitation package, which includes a sensor kit, a patient facing app, and a dashboard program for medical professionals. This system enables medical professionals to remotely monitor a patient's progress, home exercises, and rehabilitation sessions. Meanwhile, patients benefit from gamified exercise guidance, progress tracking, and the Symphysis feedback loop, which balances both the psychological and physical aspects of rehabilitation (see next section for details).
Importantly, the Symphysis system serves as a tool for both patients and medical professionals, it does not provide medical advice or directly influence the patient's rehabilitation journey. All treatment decisions remain in the hands of medical professionals. The system's primary goal is to highlight the connection between psychological states and movement to promote optimal recovery. This is achieved by measuring physiological responses to emotions related to movement, utilizing reflective methods, and administering questionnaires on illness beliefs. Additionally, it incorporates traditional assessment techniques, such as the walking test (KNFG, 2024), which can be completed remotely, allowing in person sessions to focus more on problem solving.
A key feature of the system is its unique feedback loop that the symphysis system provides, see figure 19, which helps detect early signs of psychological barriers to movement, a common issue in knee rehabilitation, particularly in later stages where balancing load and capacity is key. Fear of movement or re-injury is known to negatively impact recovery, and early detection of these psychological hurdles enables medical professionals to adapt treatment plans sooner, resulting in a more personalized approach that addresses both physical and psychological needs.
Finally, to prevent patients from becoming over-reliant on the system, the intensity of feedback can be gradually reduced over time, ensuring they regain independence and confidently return to normal activities after a successful rehabilitation.

Feedback loop

The main purpose of the symphysis system is to create a feedback loop supporting parallel recovery, see figure 20. In this feedback loop the system detects physiological changes related to movement opening the conversation with medical professionals of how emotion effects the rehabiltation of the patient.
The patient wears the Symphysis system by strapping the sensors on their injured leg and wrist. The patient follows the instructions in the app for calibrating the movement sensors. The system is able to detect daily activities, live physiotherapy and telerehabilitation sessions. if the system detects strong changes in the physiological metrics related to movement it creates an event and sends a notification to the app. in this event the patient can choose to reject the event or make a reflective note for later with a quick comment. Aditionilly the patient can go to mental exercise in the app if they desire.
In figure 20 two examples are given of a pain moment or a fear reaction to a movement. The physiotherapist can monitor progress from a distance using the Symphysis dashboard. See the data of the practice sessions at home and events that occured. This can be used to discuss the events with the patient and optimize the treatment plan completing the feedback loop

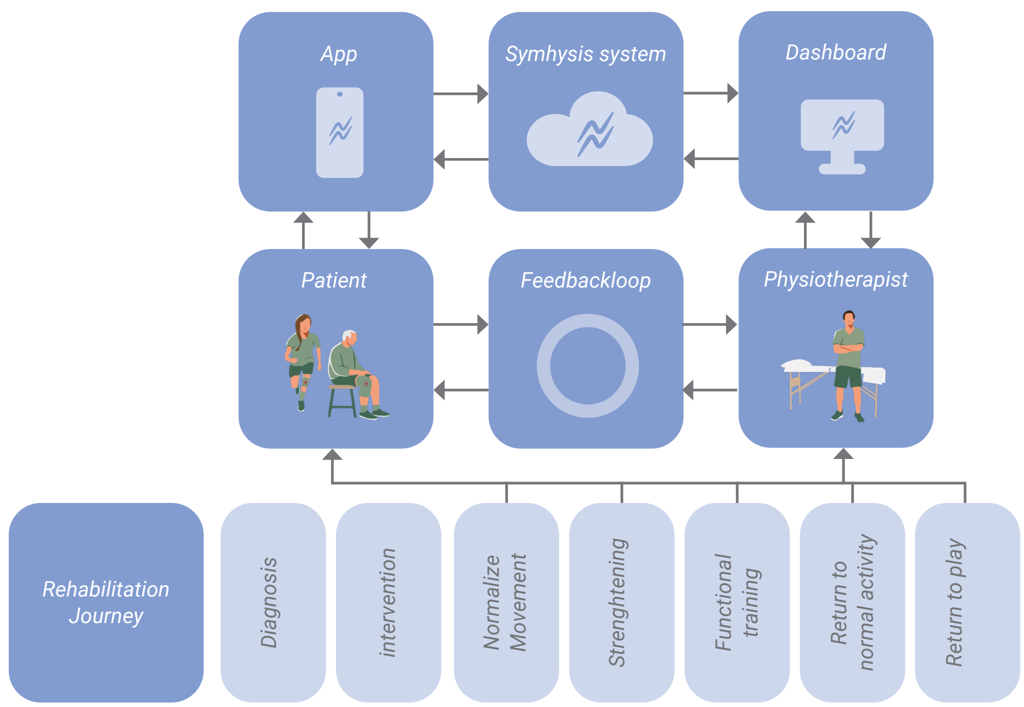


Figure 19: Integration of Symphysis in the rehabilitation journey

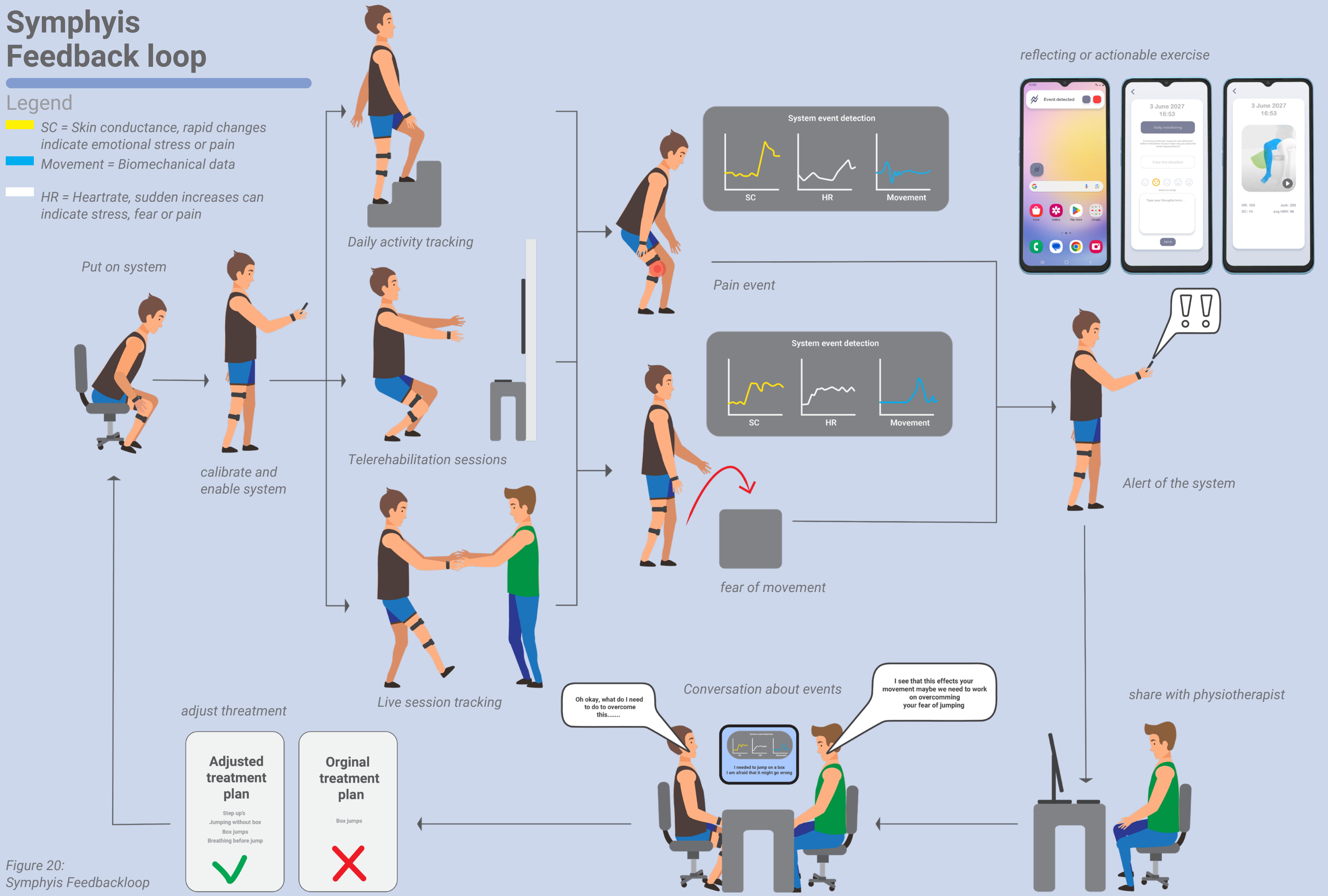


Figure 20:
Symphyis Feedbackloop

Continous monitoring

The long battery life and extended Bluetooth range of the modules make continuous monitoring possible, enabling the tracking of activities outside physiotherapy sessions. The system can monitor daily activities such as stair walking and commuting to work. Additionally, it is capable of tracking individual exercises prescribed by the physiotherapist for the patient to perform remotely.

Beyond tracking, the system's high refresh rate supports real-time motion guidance during home exercises. During physiotherapy sessions, it provides detailed insights into movement and physiological metrics, offering a valuable tool for communicating knee-related data to the physiotherapist.

Combined with the Symphysis feedback loop and event detection capabilities, the Symphysis monitoring system can be applied to a wide variety of activities.

Metrics

The Symphysis system is capable of generating a wide array of complex metrics, including biomechanical data and detailed physiological signals related to emotional arousal. However, translating these metrics into actionable insights for both patients and physiotherapists remains a significant challenge.
The main purpose of the Symphysis system is to achieve a balance between physical and emotional load and capacity. To facilitate this, a high-level overview concept has been developed, highlighting three core metrics derived from the underlying sensor data (see Figure 21):

Knee strain: This metric integrates biomechanical data related to the knee and visualizes the cumulative daily loading.

Recovery: Based on Heart Rate Variability (HRV) and the knee's rest-state measurements, this metric reflects the user's physical recovery status.

Emotional load: Utilizing HRV and Galvanic Skin Response (GSR) data, this metric provides insights into nervous system activity and emotional stress levels.

The purpose of this overview is to offer a balanced and accessible representation of the user's physical and emotional state, thereby supporting informed decision-making and behavioral adjustment.
In addition to the overview, the system can present more complex metrics through graphical visualizations, each accompanied by explanatory descriptions. This feature allows for detailed analysis and fine-tuning, particularly beneficial for clinical use. Physiotherapist-relevant parameters such as range of motion and GSR response are also included to support therapeutic evaluation and planning.

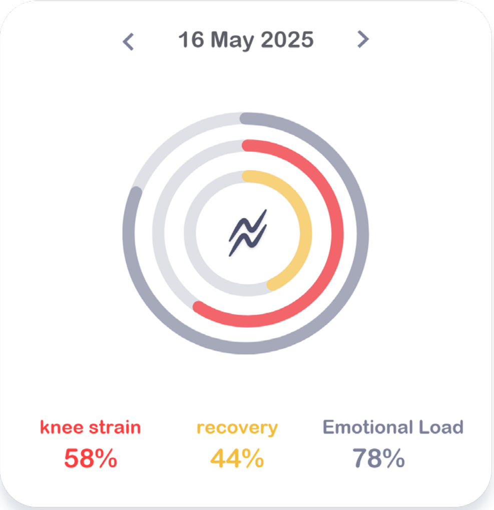


Figure 21: Actionable overview

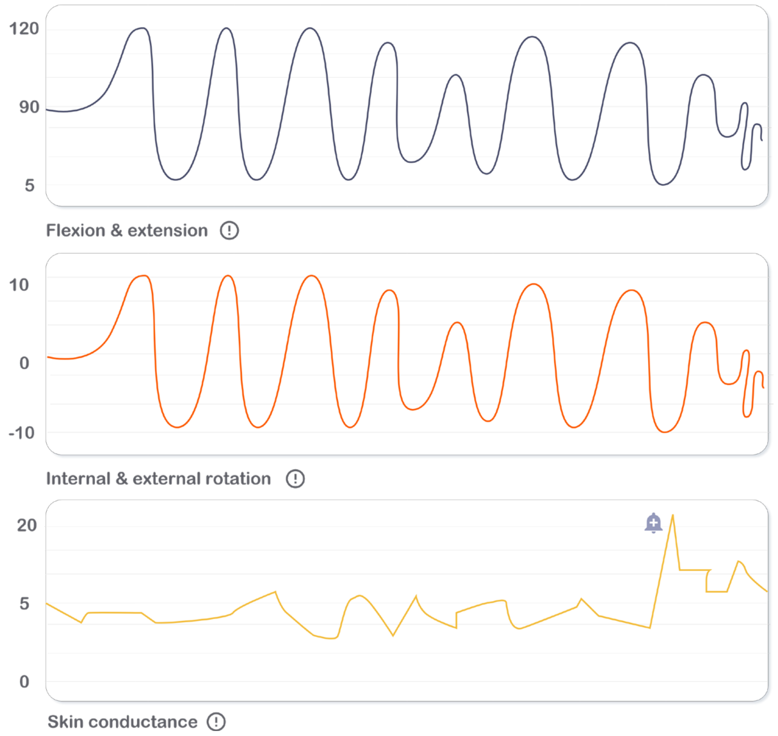


Figure 22: Example of metrics in the symphysis system

3.4. The App & dashboard

Due to time limitations, this design concept primarily focuses on hardware development. However, to fully understand how the hardware integrates into the rehabilitation process and the potential impact of the system, the user interface (UI) is also a crucial element. Therefore, a first quick impression of the supporting app and dashboard was developed. This section aims to demonstrate how stakeholders could transform the hardware's data into actionable feedback, forming an essential part of the overall product service system.

The app features an intuitive interface designed to support patients throughout their rehabilitation journey. The homepage provides quick access to the main features, including educational resources, device status, mental exercises like imagery and breathing exercises, and one of the core functions: activity tracking. Tracking serves various purposes such as monitoring daily activities, participating in live sessions, or completing prescribed exercises from the physiotherapist. The setup and calibration process is guided by easy visual instructions, ensuring that patients can get started with minimal friction. Exercises can be done using gamified, interactive guidance that keeps patients engaged and motivated.
The journaling section is where patients can engage with traditional measurement tools like the 6-minute walking test and complete an activity hierarchy designed for psychological barriers identification prescribed by physiotherapist (KNFG, 2024). This page also includes questionnaires on illness beliefs and personal reflections. An example of the activity hierarchy is shown in Figure 24, representing how the Symphysis system supports in-depth engagement between patient and physiotherapist. Completing these assessments remotely allows more time during in person sessions for personalized feedback and problem-solving.
Additionally, if the system detected events, such as deviations in Jerk, ROM or physiological stress patterns are displayed in this journaling area. Patients can select an event to open a dedicated reflection screen, where they can replay the moment, annotate it, and share their insights with their physiotherapist. This feature strengthens the feedback loop and supports a more collaborative and personalized recovery experience, see page 62,63 for an example scenario.
The app also includes a "Roadmap" feature where patients can set and track their rehabilitation goals together with their physiotherapist. These goals are fully customizable and adapt to the patient's recovery pace. Within the metrics section, users can view both physical and physiological data, such as joint loading patterns, physical activity levels, heart rate variability (HRV), and skin conductance, providing a comprehensive overview of their mental and physical recovery. This insight empowers patients to focus on specific areas of their rehabilitation process.
A calendar view is included to visualize progress over time. It shows daily metrics and streak goals, offering a macro-level view of the journey and introducing gamification elements to keep patients engaged and motivated.
On the physiotherapist's side, the dashboard offers a clear overview of all patients. Therapists can review system-detected events, monitor progress remotely, and continuously update exercises and questionnaires based on detailed movement and physiological data.

**Together these elements like real-time monitoring, gamified exercises, progress tracking and a continuous feedback loop create a holistic and interactive user interface. The Symphysis system empowers both patient and physiotherapist to work in parallel, integrating physical and physiological insights into a streamlined and intuitive rehabilitation experience.
The UI/UX design needs further development and design iterations in the future, but the first impression in figure 23, 24 is a fisrt step for further developent. For an example scenario see page 62, 63.**

Figure 23: First quick impression ofthe dashboard

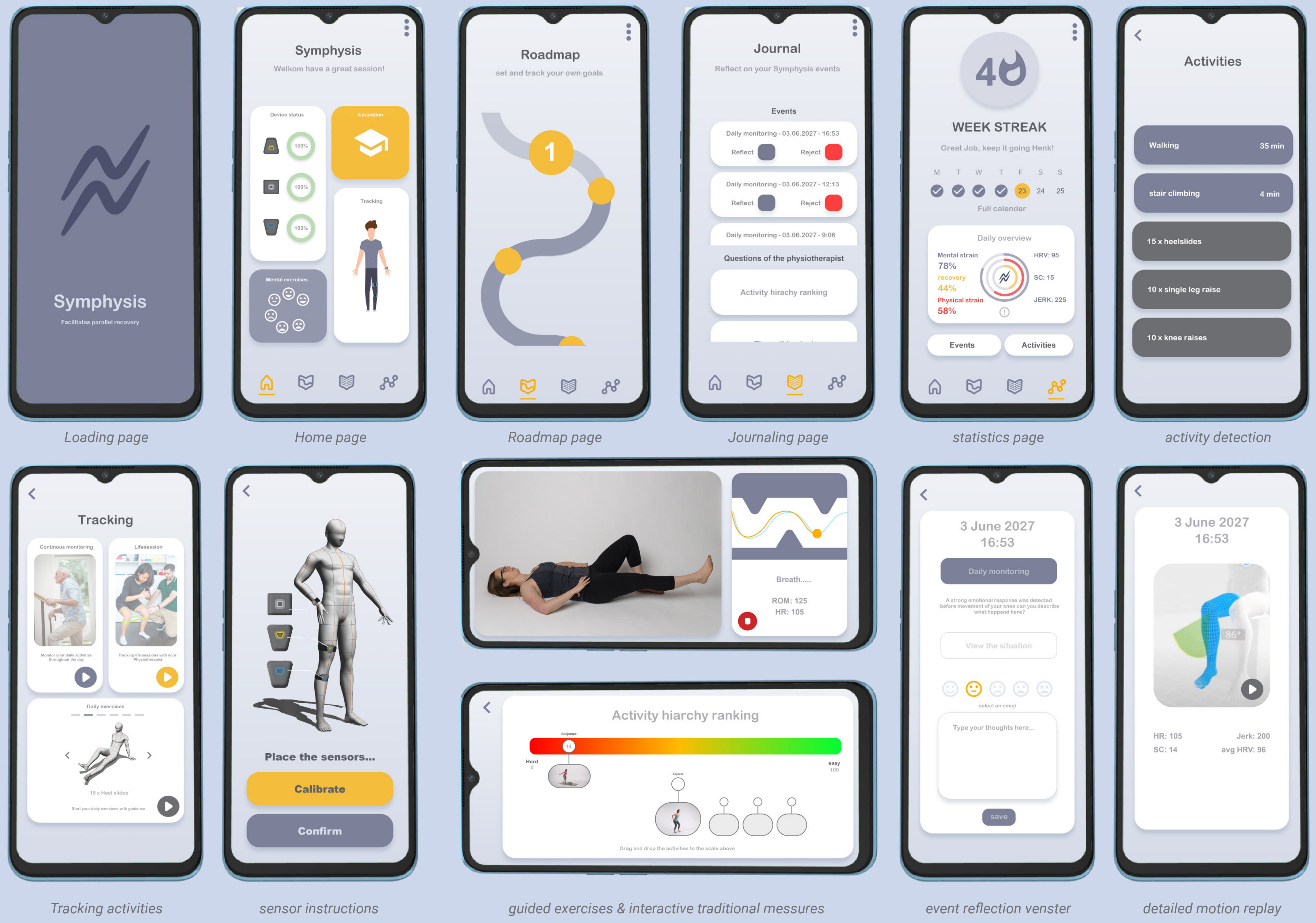
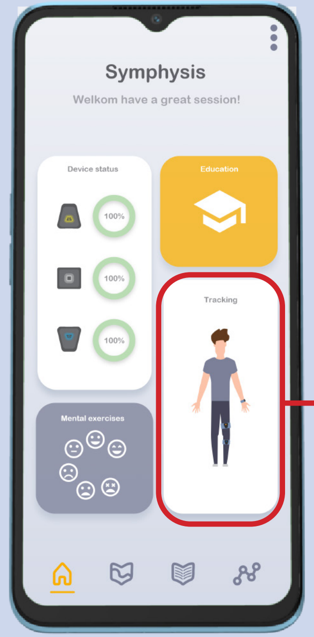


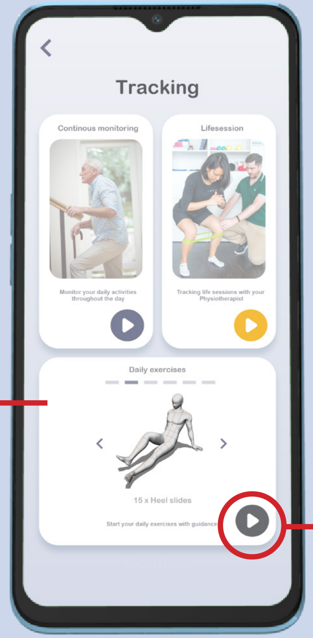
Figure 24: First quick impression of the App

Example scenario

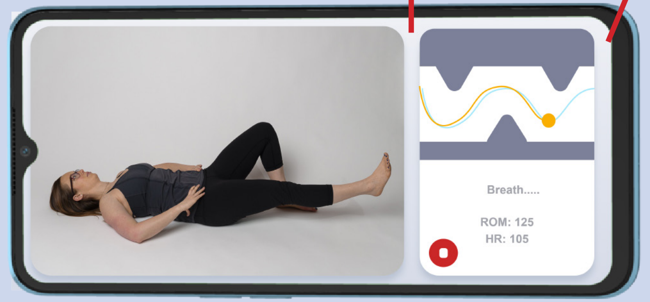
This section clarifies the app & dashboard design by giving an example scenario of how the app and dashboard use is intended. In this scenario a patient decides to do the daily exercises provided by the physiotherpasit with help of the symphysis system.



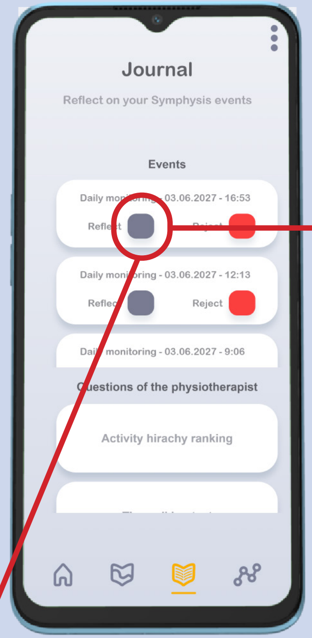
On the home page, can check the device status of the modules and choose the tracking option.



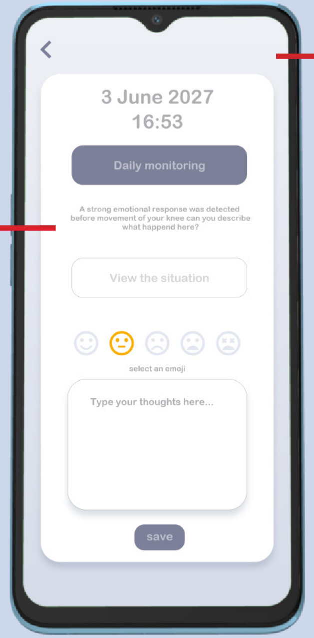
On the tracking page the user can choose physio live sessions, daily tracking and performing daily exercises. In this scenario the user chooses the daily exercises option



The user can do guided exercises with the app and stream it to a television. During this session an event is detected. the patient had a strong emotional response during the heel slide exercise. This event is stored in the journaling page.



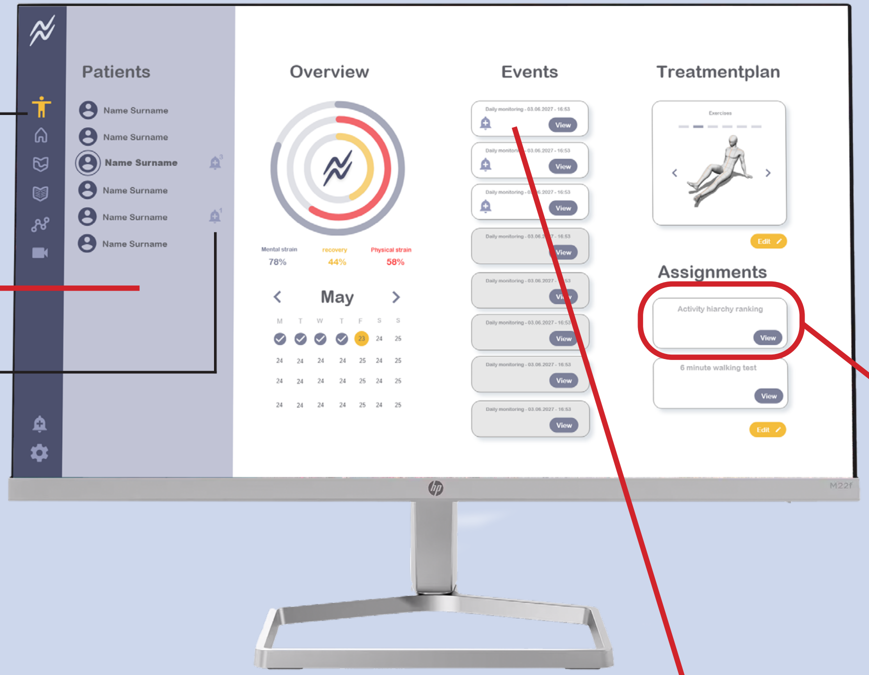
In the journaling page the patient can choose to reject an event or reflect on the movement



the user reflects about the event that happend. chooses a smiley and types "First it was going great but then i heard a "click" and I was afraid to move my knee again".

Patients

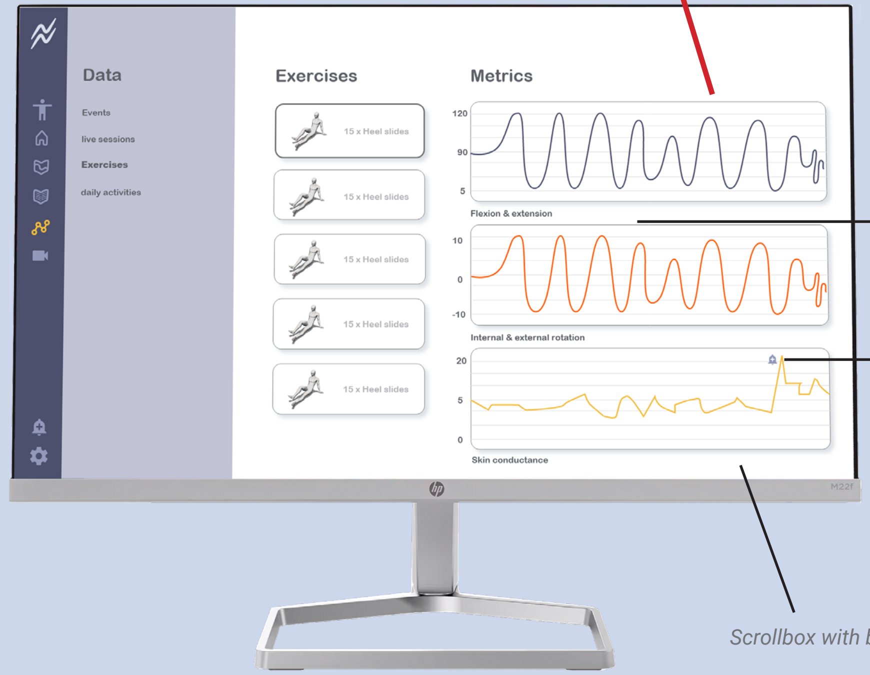
Event alerts



The physiotherapist sees the triggered alert and can analyze what happened on the dashboard in the context of the daily overview.
In this case, there is an alert related to the daily exercises, so the physiotherapist can view the detailed metrics and examine the event. A high skin conductance was detected in relation to movement, which could indicate strong emotional arousal. The patient also reported experiencing fear.

The physiotherapist wants to understand more about how the patient cognitively perceives activities. Therefore, the physiotherapist assigns the patient a task in the app: to complete an activity hierarchy, ranking activities by difficulty on a scale from 0 to 100.

The patient fills in this assignment ready to discuss during the next consultation



analysing the movement before and after trigger moment suggest a reduced range of motion repitition followed by a strong emotional response and stop consistent of movement

trigger event

Scrollbox with biomechanical messures and physiologcal signals

3.5. Technical working

In the previous sections parts and the use of the Symphysis system is explained. In this section the technical working principles of the sensors are explained and how they generate valuable data for the system by working together. A visual representation of these technical working principles is displayed in figure 25.

Detecting knee movement

The Symphysis sensor kit includes two sensor modules, one attached to the thigh and the other to the shin. These modules have an electronic circuit equipped with a 9-axis inertial measurement unit (IMU), which consists of an accelerometer, a magnetometer and a gyroscope. The IMU measures acceleration, magnetic field strength, and gyroscopic data in three dimensional space. By integrating data from both IMU modules using mathematical models, the system is capable of accurately tracking knee angles in real time, see software section in 4.1

The sensors operate at a frequency of 200 Hz, allowing for high resolution motion tracking suitable for telerehabilitation and real time feedback or gamification. This precision enables healthcare professionals to analyze gait patterns and biomechanical parameters, including range of motion (ROM), velocity, acceleration, and jerk. Furthermore, the system can assist in daily activity monitoring like workout intensity and activity detection such as walking, stair climbing or even falling.

Detection of Physiological Metrics

Physiological metrics are measured using the wrist module within the system. This module includes a galvanic skin response (GSR) sensor that measures skin conductance by detecting variations in electrical resistance, which correlate with autonomic nervous system activity. Additionally, the system integrates three photoplethysmography (PPG) sensors that monitor heart rate (HR) and heart rate variability (HRV). PPG sensors work by emitting red and infrared light through the skin and measuring changes in blood flow using a photodetector (Maxim Integrated, 2018), see figure 25. By using multiple sensors, the system minimizes errors such as skipped beats, therefore improving measurement accuracy.

To further improve the reliability of physiological measurements, the wrist module is also equipped with an IMU. This IMU enables movement compensation algorithms that adjust GSR and PPG readings based on wrist motion, reducing the impact of hand movements. By integrating inertial data, the system ensures more precise physiological monitoring, even in dynamic conditions.

HRV analysis is performed by detecting RR intervals (the time between successive heartbeats), allowing the calculation of parameters such as the root mean square of successive differences (RMSSD) and the standard deviation of normal to normal intervals (SDNN). These metrics provide insights into autonomic nervous system function and emotional arousal (shaffer, F., Ginsberg, J.P.,2017). The wrist module also incorporates temperature and humidity sen measures sors, which help optimize GSR measurements by compensating for environmental influences. Variations in temperature and humidity can affect skin conductance due to thermoregulatory processes therefore influencing detection of sympathetic nervous system activation.

As explained in Chapter 1, GSR, HR, and HRV are frequently used to assess physiological responses to emotional stimulance. By analyzing these signals, the system can detect variations in autonomic nervous system activity, which may indicate emotional responses such as stress, anxiety, or pain.

Integration of Movement and Physiological Metrics

The Symphysis system combines motion tracking data with physiological responses to assess emotional and physical reactions related to knee movement. For instance, a sudden deceleration with a high jerk value, coupled with an abrupt increase in GSR and HR, may indicate a pain response. Additionally, fear related movement avoidance can be detected by identifying an elevated GSR and HR response prior to motion initiation. By recognizing these patterns, the system can trigger specific alerts or interventions, enabling healthcare professionals to better understand patient responses and tailor rehabilitation strategies accordingly.

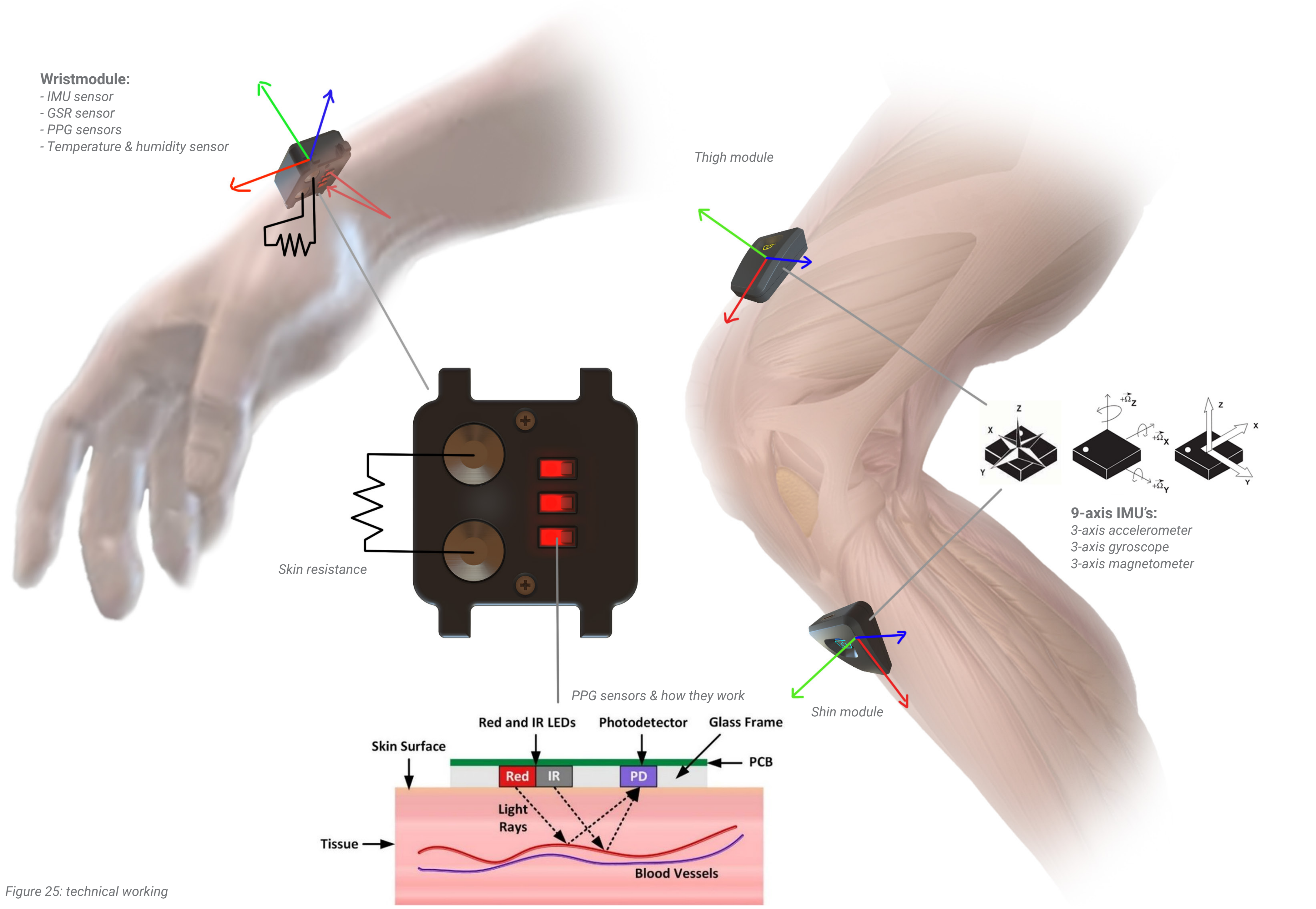


Figure 25: technical working

3.6. Hardware design

The hardware consists of two seperate elements: The straps that are used to put the Symphysis system on the body, and the three hardware modules. In this section the design of these two elements are explained including, the form & aestetics, functional considorations and the manufactoring and assembly process of the hardware elements.

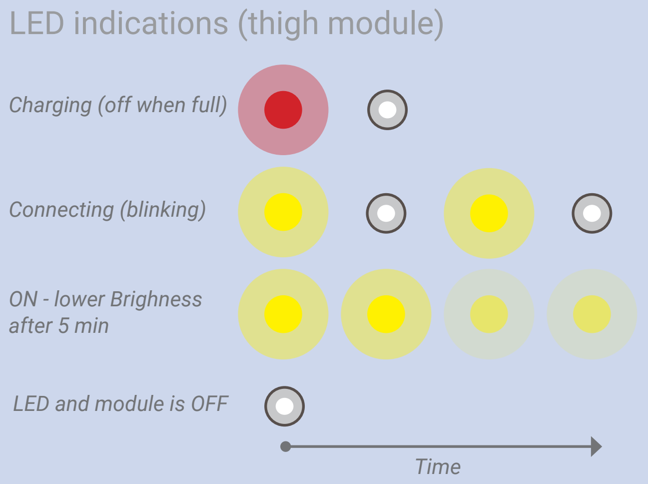
Modules

The design of the Symphysis Modules follows a consistent form language across all three modules, reinforcing their visual and functional coherence as part of a system. The dark grey satin finish provides a neutral yet professional aesthetic, enhancing both usability and perceived quality.
The Thigh and Shin modules share an identical shape, ensuring a seamless integration with the body and minimizing differentiation in placement. The Wrist module, while distinct in shape due to its different functionality, maintains the same overarching form language, ensuring a cohesive system identity. The form of each module is designed to optimize human interaction and enhance user comfort during wear.
The two IMU modules feature an asymmetric shape that serves a dual purpose: facilitating intuitive placement within the strap pocket and providing clear orientation cues in the application. Additionally, the sloped surfaces of these modules enable clothing to glide smoothly over them, reducing the risk of clothing catching on the module and allowing for wear underneath clothing (see figure 27).
The Wrist module incorporates an asymmetric button placement, ensuring intuitive operation and minimizing user errors in application. Furthermore, the interface of each module is intentionally simple, prioritizing ease of use. Each module is equipped with a USB-C port for charging the internal battery, as well as an ON/OFF button with LED indicators for status feedback. The LED indicators employ three distinct colors: blue, yellow, and white. Research has demonstrated that blue and yellow offer optimal differentiation across the visual spectrum, including for colorblind individuals (Mullen, 1985). The LED interactions are as follows:

- Charging: When charging, the LED turns red; upon full charge, the LED turns off.
- Searching for Connection: A fast-blinking LED indicates an active search for a connection, activated by a short press of the button.
- Connected: A steady LED indicates a successful connection. After five minutes, the LED dims to a low-brightness state to conserve power.
- Power Off: The module is turned off by a long press of the button.

To prevent accidental activation during physical activities or unexpected impacts, all module buttons are slightly recessed into the surface. This design choice ensures reliability during rehabilitation exercises.

Figure 26: Module design



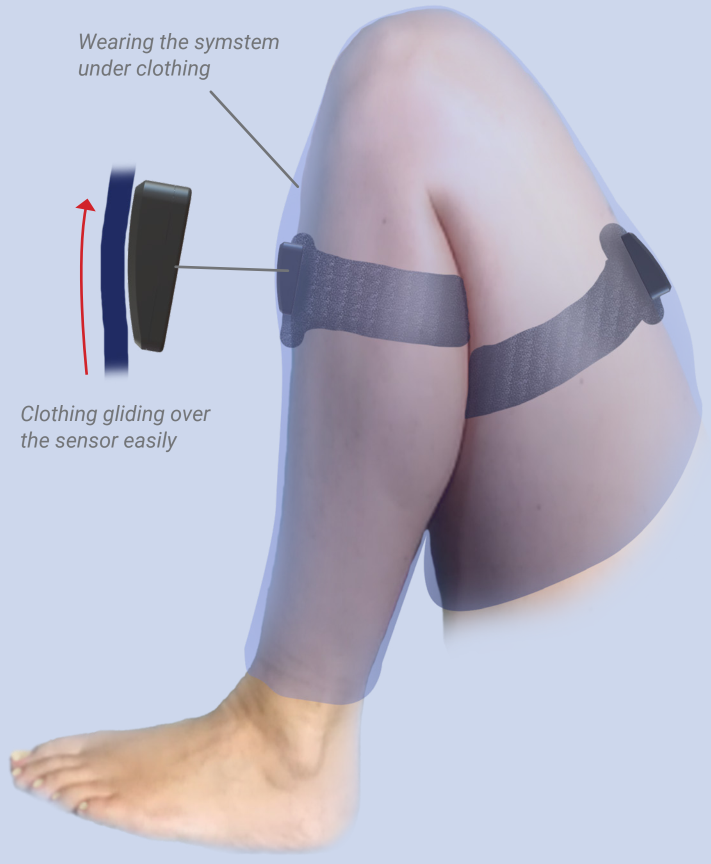


Figure 27: wearing the system underneath clothing

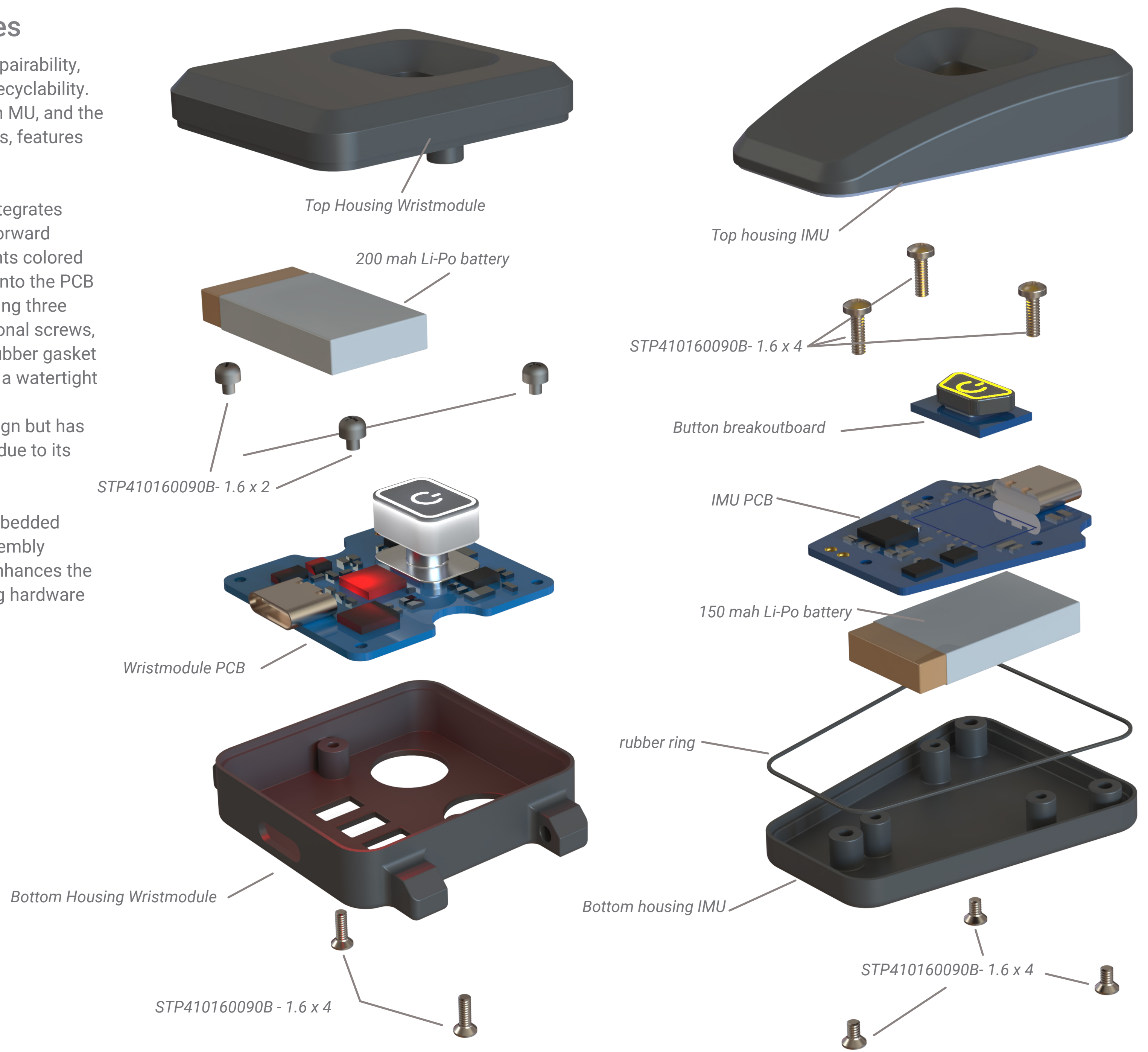
Modules on the body

Assembly of symphysis modules

The design of the system's modules prioritizes repairability, facilitating ease of maintenance, upgrades, and recyclability. Each of the three modules, the shin IMU, the thigh MU, and the wrist module equipped with PPG and GSR sensors, features lighweight and accessible assembly.

The IMU modules incorporate a Main PCB that integrates a button breakout board, facilitating the straightforward replacement of colored LED buttons for the diffents colored indication LED's. A 150 mAh battery is soldered onto the PCB and mechanically fastened within the housing using three screws. The enclosure is sealed with three additional screws, accessible from the bottom, which compress a rubber gasket between the two housing components, achieving a watertight seal.
The wrist module follows a similar structural design but has more space for a slightly larger 200 mAh battery due to its expanded internal space.

The housing design's incorporates accessible embedded screws, allowing for easy disassembly and reassembly without damaging components. This approach enhances the system's longevity by simplifying repairs, enabling hardware upgrades, and promoting material recycling.



straps

The straps of the symphysis system are designed for durability and ease of use. The wrist module straps are similar to 18 mm smartwatch straps, featuring two small arms where a spring bar secures the strap in place. These straps are interchangeable, allowing users to customize them according to their preferences. They are available in both silicone and fabric options. The adjustable holes in the strap ensure a secure fit around the wrist, optimizing skin contact for the sensors in the wrist module.

The IMU straps are made from a stretchable material, ensuring a comfortable and secure fit around the leg. At the start of each strap, there is a dedicated pocket for the IMU module. This pocket is designed with the same asymmetrical shape as the module itself, serving as an intuitive guide for correct orientation. The strap can be easily tightened by pulling it around the leg, threading it through a reinforced plastic guard, and securing it with Velcro. The plastic guard prevents fabric wear and tear when the strap is under tension, ensuring longevity and reliability.

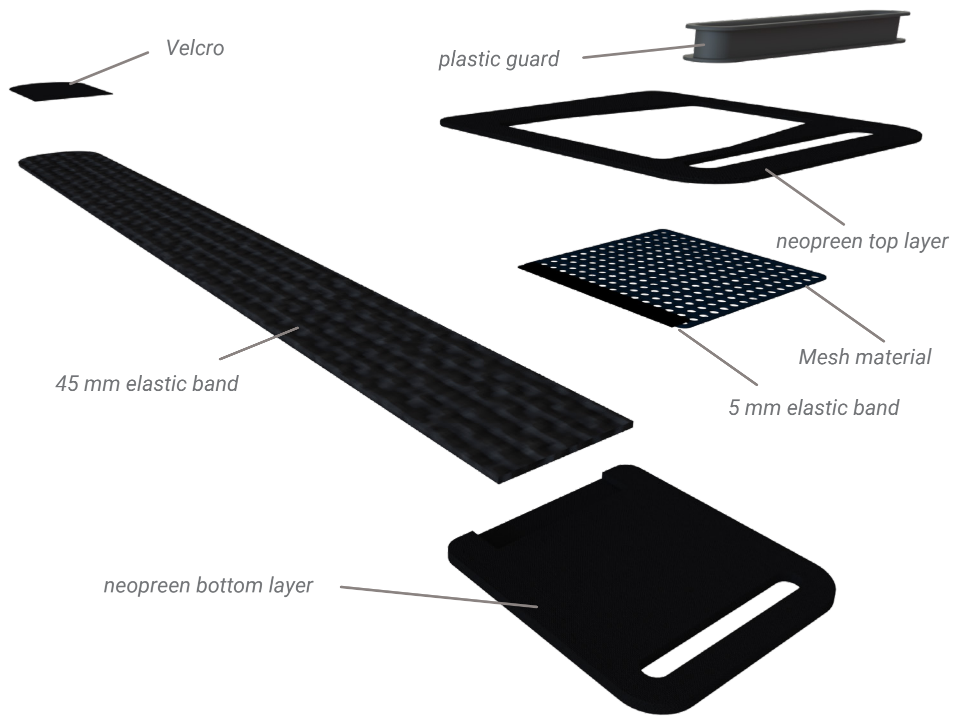


Figure 28: assembly of IMU strap

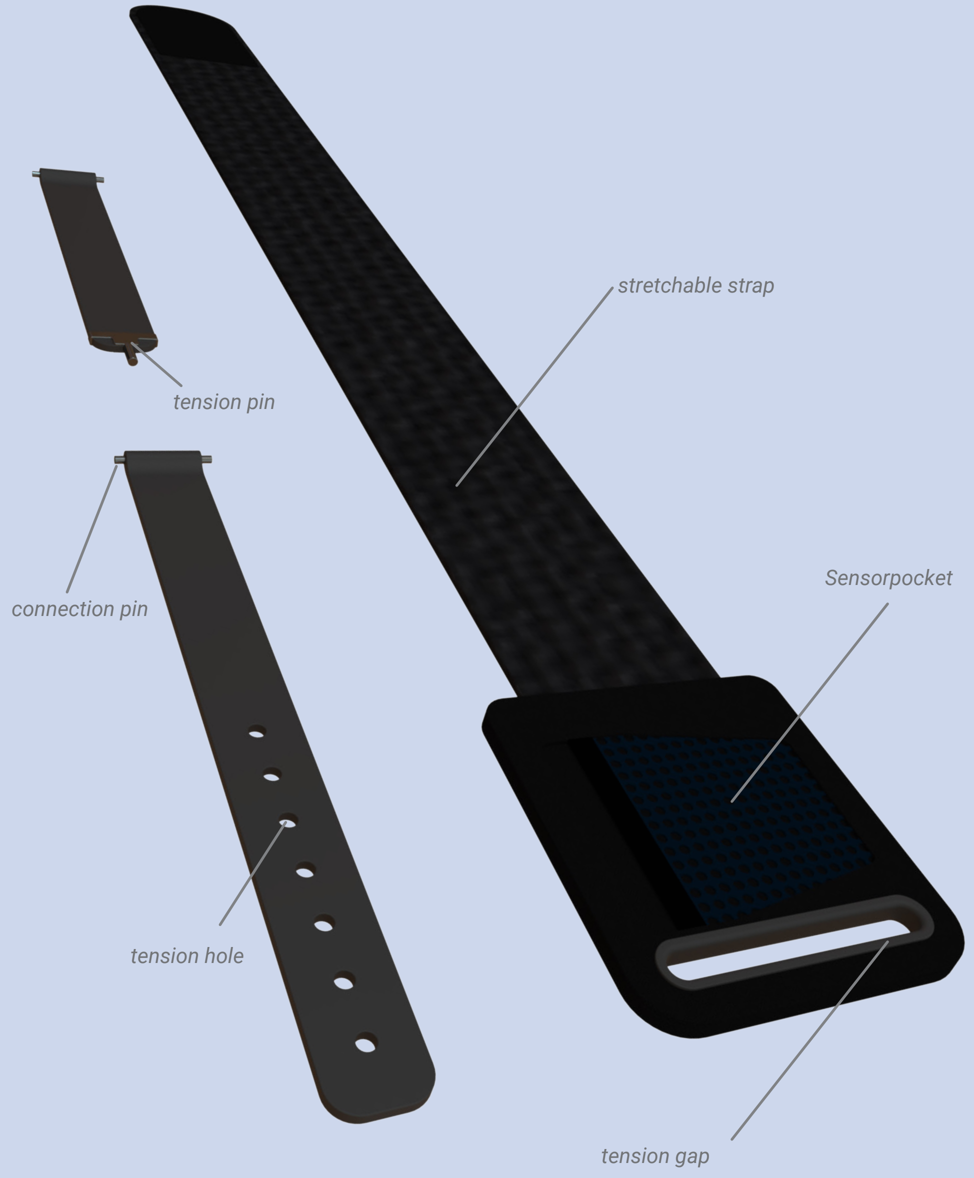


Figure 29: Ddesign of the straps

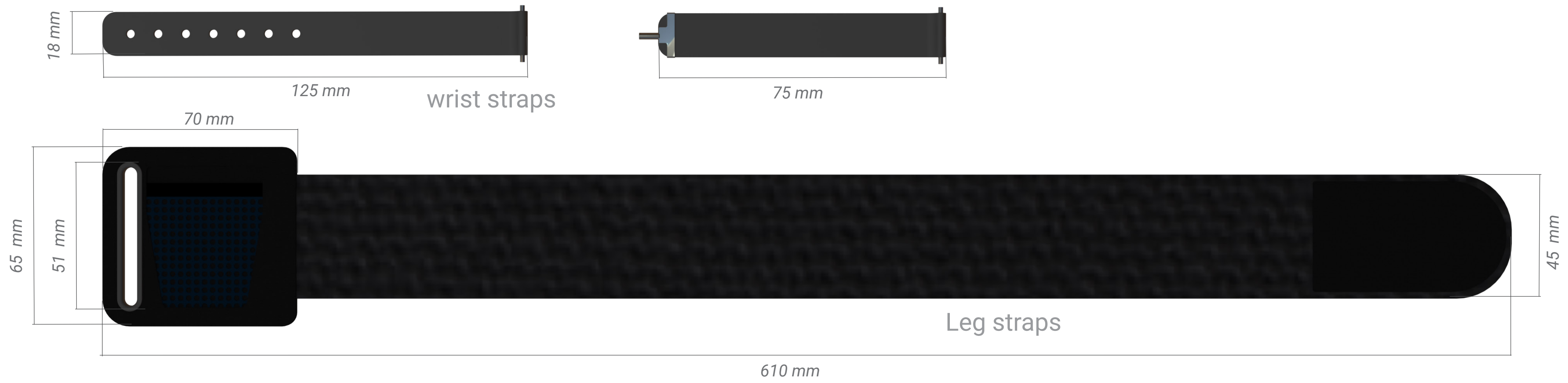
Mesurements

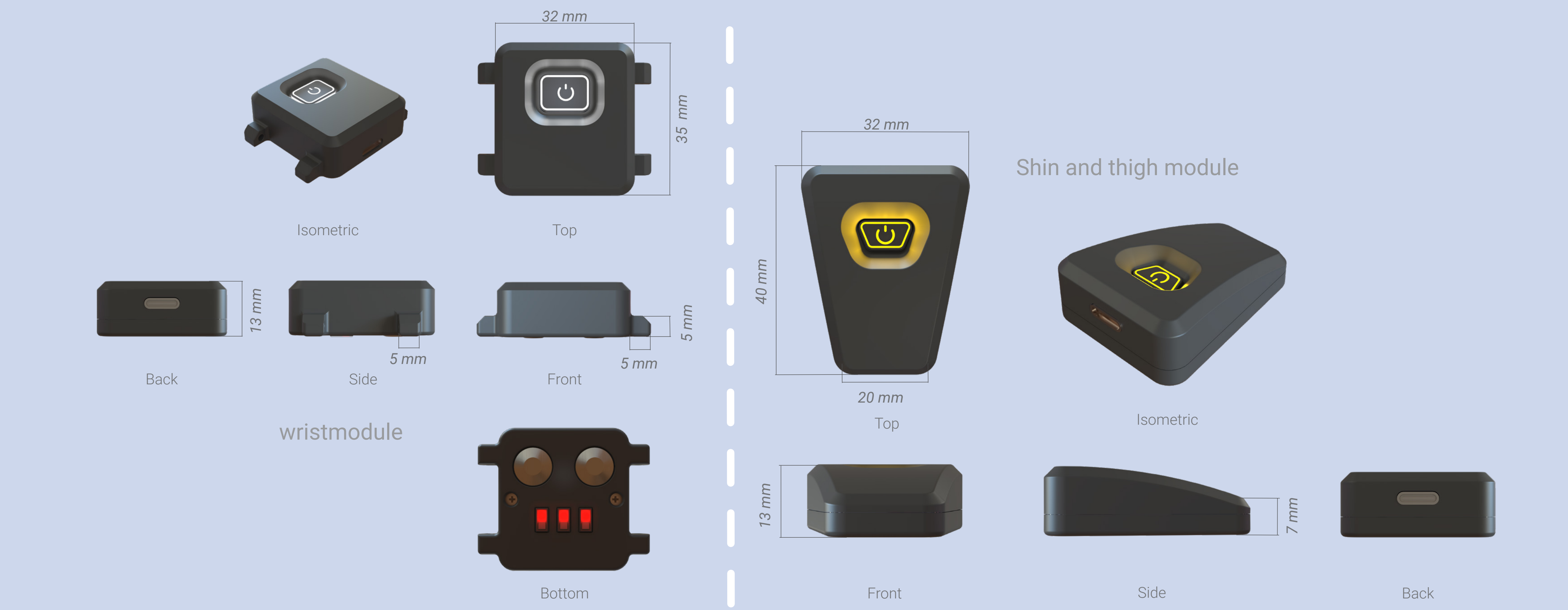
Using the anthropometric data in Chapter 1.1, the wearable system is designed to fit 90% of the population. This section details the considerations for sizing the straps and modules, ensuring both optimal performance and seamless integration of functionalities.

During knee rehabilitation, the leg has size changes due to swelling, muscle growth, and shrinkage. To account for these variations, the leg straps are designed to fit the maximum thigh circumference, with a 610 mm elastic strap that includes a sensor pocket. This elastic section allows for further stretching, ensuring a secure fit. The loopthrough design allows for flexible velcro placement along the back of the strap, allowing for adjustments based on patient leg sizes. For smaller patients or shin placement, the velcro can be wrapped further around the leg, allowing for double wrapping, making sure that the larger strap length does not become an issue.

The wrist module straps are designed to fit various wrist sizes and are interchangeable with standard 18mm smartwatch straps. Additionally the strap is adjustable, ensuring enough tension to keep the sensors securely in place.

The module sizes are optimized to balance battery capacity, weight, and functionality. Their compact design allows them to be worn discreetly under clothing. Additionally, the minimal height and low center of gravity reduce inertia relative to the skin, leading to more accurate sensor readings.





3.7. Manufactoring

This section outlines the estimated manufacturing process for the Symphysis sensor kit. Further coordination with suppliers will be required to refine and optimize the final workflow.

Modules

The housing parts of the modules are designed to be 3D printable with minimal support requirements, optimized for both SLA and FDM printing during the first production phase. Additionally, the housings incorporate a 1degree draft angle, making them suitable for injection molding in larger-scale production. Wall thickness has been standardized at 1 mm for this purpose. The material is ABS-PC for procesability, lightweight and high impact resistance.
The electronics within the modules will be manufactured using custom-designed PCBs with standard off-the-shelf components. These include sensors, USB-C ports, buttons, and other elements.
Custom rubber seals (0.5 mm thick) will be produced using rubber extrusion, cut to the required circumference, and then vulcanized (heat-fused) at the ends to form continuous sealing rings.
Other components such as screws, support cables, and batteries will be sourced from external manufacturers.
Assembly of the modules includes:

- Soldering batteries to the PCBs
- Flashing firmware onto the PCBs
- Soldering breakout boards onto the IMU PCBs
- Mounting the PCBs into the bottom housing using screws
- Assembling the housing with screws and integrating the rubber seal

For further detail, refer to the “Assembly of Modules” section in 3.6. Hardware Design

Straps

IMU module straps will be made using 45 mm elastic stretch band, purchased by the meter and cut to length. A strip of Velcro will be sewn onto one end to complete the adjustable fastening system.
The sensor pocket will be assembled using two layers of neoprene fabric cut to shape. Sandwiched between these layers is an elastic band combined with mesh material, creating a breathable and flexible pocket for the sensor. These layers are joined using a sewing machine.
A plastic guard, produced using 3D printing or injection molding, will be attached to the end of the sensorpocket in the hole. This allows the elastic band to glide smoothly through the opening on the edge of the sensor pocket without tear.
Wrist module straps will be sourced from a third-party manufacturer producing 18 mm smartwatch straps with a spring-pin mechanism.

others

Charging cables and power adapter will be externally sourced and customized using a sticker with the Symphysis logo. The carrying case will be sourced from a headphone case manufacturer, and a custom-cut foam insert will be used to securely hold all components of the sensor kit.

3.8. Cost & price estimation

To assess the market viability of the Symphysis system, a cost estimation of the hardware components was made. This estimation can be used in comparison with existing market alternatives and provides more information for setting a competitive and sustainable pricing strategy.

hardware production cost

In order to make good estimation of the hardware cost a batchsize of 10.000 units was used for calculating unitcost, for a full breakdown of parts and assembly see appendix W. Manufactoring will be outsourced to China, not only for the lower labor cost but also due to the acces to manufactoring industry infrastructure and expertise nearby including, batteries, PCB assembly, affordable injection molding and assembly companies.
In table FIXME are the estimated costs for producing the complete sensorkit. this comes to arround ~€115 per kit. This includes materials, electronic components, labor for assembly and testing procedures, see table 6.

Investments

Before production of the hardware can start investments need to be made consiting of injection molds to produce the casings for the modules. For the injection molding proces four seperate small aluminuium open molds are needed each ranging from 5500 to 6500 euro depending on tooling complexity, see table 7 This requires an investment of 22000 to 26000 euro. These cost are already included in the price of the parts.

Development and validation

While the hardware forms the physical function of the product service system, Symphysis is a product-service system combining sensor hardware with software and clinical functionality. As such, development and clinical validation, such as CE and ISO standards, are significant contributors to the overall cost and value proposition.
Software development, including the patient mobile application, gamified rehabilitation modules, and therapist dashboard still needs a lot of development in collaboration with medical institutions. These cost still need to be calculated and included in the final pricing of the product. for now an extra €50 - €100 per sensorkit is included to aacount for these costs.

The price of the symphysis hardwarekit will come to arround €499,99 per sensorkit. this esures healthy margins of around ~130%. This price accounts for production cost and a rough estimation of development cost included. However further validation of this price is needed especially on the software development and validation cost.

Symphysis Hardware	*Cost*
Thigh module	*€ 27,30*
Shin module	*€ 27,30*
Wrist module	*€ 36,20*
straps	*€ 12,80*
charger + bag	*€ 6,10*
Packaging + overhead	*€ 6,00*
Total	*€ 115,70*

Table 6: hardware production cost

Investments	*Costs*
Wrist housing bottom mold	*€ 5500 - 6500*
Wrist housing top mold	*€ 5000 - 6000*
IMU housing bottom mold	*€ 5000 - 6000*
IMU housing top mold	*€ 5000 - 6000*
Total	*€ 22.000 - 26.000*

Table 7: Hardware investments

Factor	*Cost*
Production cost	*€ 115,70*
Development cost	*€ 100*
~130% margin	*499,99*

Table 8: Cost price estimation

3.9. Market viability

As analyzed in Chapter 1, the field of physiotherapy is experiencing a fundamental shift driven by technological advancements, an increasing shortage of healthcare professionals, and evolving patient needs. The integration of AI and machine learning is accelerating innovation in digital rehabilitation and E-health technologies, with players such as Eularia Health and Sword Health in movement tracking and telerehabilitation systems. However, these solutions mainly focus on clinical biomechanical parameters, leaving critical psychological dimensions of recovery unaddressed.
Qualitative interviews with patients underscore a gap in current rehabilitation solutions: many individuals face psychological challenges such as fear of re-injury, lack of confidence and negative beliefs about their condition. These barriers, while less visible, are crucial in determining the success of physical rehabilitation. Unfortunately, with patients becoming more reliable on themselves during rehabilitation with home exercises and telerehabilitation these barriers become less visable.

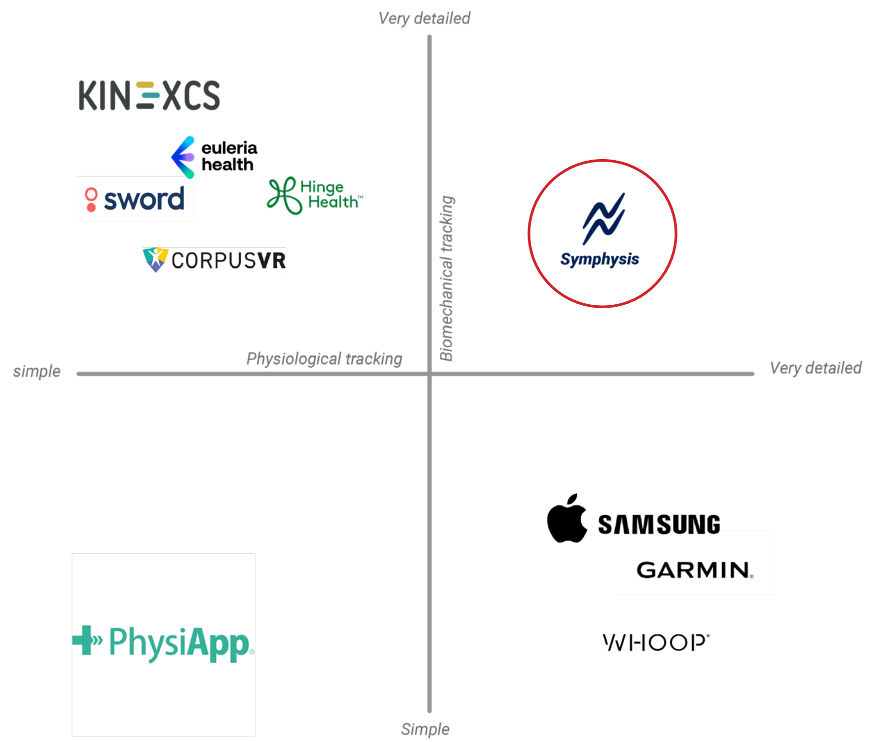
Symphysis addresses this unmet need with a holistic, hybrid solution: The system not only captures detailed movement data but also integrates emotional and cognitive feedback to foster reflective engagement. Macro gamification strategies, such as progress streaks, guided exercises, and visual tracking boosts adherence and patient motivation, making recovery more interactive, personalized load vs capacity managements and opens the conversation with healthcare proffesionals about the psychological and physcal challenges in rehabiltation.

The hardware is priced competitively at €499, placing it well within the range of comparable sensor-based rehabilitation systems (€500–€2000), many of which lack integrated psychological support. The software is envisioned as a software as a service (SaaS) platform, enabling physiotherapy clinics to license the system through subscription models. This opens the door to recurring revenue streams and long-term partnerships, particularly in a B2B setting with rehabilitation clinics and insurance providers.

Strategic Market Entry & Expansion

For market entry, Symphysis proposes a two way approach. First, targeting professional athletes and sports clinics for a beachhead market. In this high performance environment, the value of rapid recovery, injury prevention and performance optimization is clearly understood and heavily invested in. Success stories in this domain can serve as a powerful marketing tool, while funding further development of the product.
Second, partnering with insurance providers and healthcare systems supports the longer-term B2B strategy. If clinically validated, Symphysis has the potential to improve adherence, shorten recovery timelines, and reduce total rehabilitation costs. This positions the product as a value-based solution capable for insurance reimbursement, especially as healthcare providers seek scalable technologies to address growing demand with limited medical professionals.

In summary, Symphysis is uniquely positioned at the intersection of physical rehabilitation, psychological well being, and digital innovation. Its differentiated value proposition, competitive pricing, and dual B2B strategy targeting both elite performance and institutional healthcare create a solid foundation for market entry and long-term growth.



3.10. Reccomendations

The Symphysis product-service system is currently a conceptual design that still requires extensive validation and development before it can be brought to market. The following steps outline the critical path towards transforming Symphysis into a clinically approved rehabilitation tool.

The first step is evaluating whether the Symphysis sensor kit is technically capable of detecting physiological changes associated with knee movement in a controlled laboratory setting. This stage focuses on validating sensor accuracy, signal consistency, and overall hardware functionality.
Upon successful lab testing, the next phase includes designing the circuit boards and producing all necessary components for a fully functional prototype. This prototype must meet quality and safety standards to be eligable for future certification and clinical trials.
Exploring collaboration opportunities with existing wearable technology platforms, such as IMU devices from Witmotion and Movella or smartwatches that may integrate GSR sensors in future versions, could accelerate development and improve cost-efficiency. Partnering with established hardware ecosystems may also enhance reliability and reduce the need for custom hardware production.
Parallel to hardware development, the UI/UX design of the Symphysis system must be created to ensure a seamless and engaging experience for both patients and healthcare providers. At the core of the software platform is an AI- and machine learning-driven feedback loop, capable of interpreting movement data and delivering personalized insights. This process should be developed in close collaboration with physiotherapists to co-create guided exercises and adaptive treatment plans.
Once the system is technically validated and a functional prototype is developed, clinical trials must be conducted to test Symphysis in real rehabilitation scenarios. These trials need appropriate ethical approval and medical certification to ensure safety and efficacy in the knee rehabilitation process.
Following successful clinical validation, the system can be released for use in knee rehabilitation. Post-market feedback will be crucial for continuous improvement
In the long term, Symphysis aims to become a modular physiotherapy tool applicable across various rehabilitation contexts. By supporting a range of conditions, the system can provide a more holistic and adaptive recovery experience for multiple rehabilitation needs.

Due to the complexity of the Symphysis system, it is not feasible to complete the entire development process within the timeframe of this graduation project. Therefore, this study will focus specifically on the first development stage: the technical validation of the hardware in a laboratory environment. This includes assessing whether the system can detect physiological changes during knee movement and investigating the relationship between these physiological signals and joint mobility. The outcomes of this validation phase will be discussed in detail in the following chapter (Chapter 4).

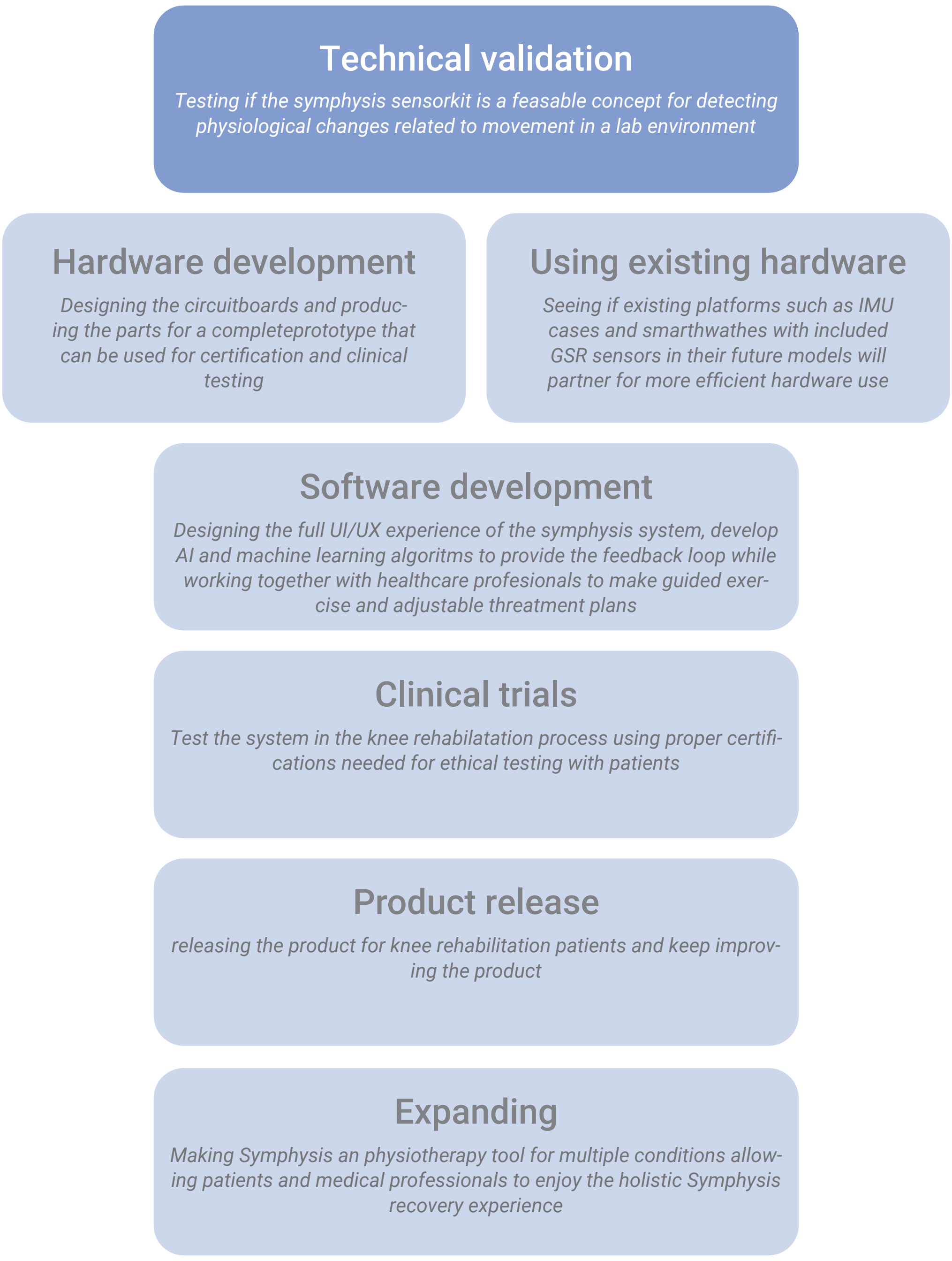


Figure 30: Roadmap for product development

4. Validation

In the previous chapter the product design of "Symphysis" was explained in detail. In this chapter the validation of this concept will be described, including the creation of a functional prototype with supporting testsoftware to accommodate a quick usertest exploring the technical feasibility of the system detecting emotional signals in relation to knee movement. Aditionally some validation on user interaction and understanding metrics for the application has been done. The findings in this chapter can be used to acces if the technological approach of "Symphysis" is worth exploring further and what the further steps and reccomendation are.

4.1. Functional prototype (HI-FI)

In this section the creation of the functional prototype is explained. The functional prototype will be used to validate the concept described in chapter 3 on feasibility. In order to judge if Symphysis is able to detect emotional arousal in relation to knee movement both hardware and software prototypes were created to gather the relevant data during user testing, see user test study on page 84.

The final prototype consists of hardware and software. The hardware needs to be integrated in a way such that the sensors can provide reliable signals. While the software needs to translate these signals into the relevant metrics. For the design iterations for this system see appendix S.

Hardware

The hardware prototype simulates the three modules of the wearable system. For prototyping standard sensors and controller board were used to simulate the functionality of Symphysis. The hardware created for the functional prototype are displayed in figure 31. Each module is capable of transmitting the data they collect via Bluetooth Low Energy (BLE) at 200hz.

The standardized hardware that is used:

- 2 x Witmotion 9011DCL 9-axis IMU
- GY MAX30102 PPG sensor
- Grove GSR sensor
- Arduino Nano 33 IOT
- Switch
- Adafruit Powerboost 1000C
- 1200 mah Lipo battery
- Jump wires
- 3D printed casings
- Weight lifting wrist strap
- 2 x Modified Nintendo leg strap

The two IMU's where placed in a 3D printed case to represent the design of Symphysis IMU's (slightly larger proportions) that has some better intuitive placement cues in its form language, see figure 34.
For placement on the body two Nintendo leg straps were modified to fit the size of the IMU's. For identification of the two modules two stickers are applied to the case (Blue, Yellow).
The Wit motion 9011DCL 9-axis IMU's have a 3-axis accelerometer, gyroscope and magnetometer on board. These sensors are used to measure the exact position of the modules. These sensor values can be used to compare the shin module and the thigh module to measure the exact position of the knee in real time in the software.

The wrist module was made to measure the physiological responses to emotions. The wrist module is simulated by a weightlifting strap that has been modified in order to house the GY-MAX30102 PPG sensor and the Grove GSR sensor contact points, see figure 31. The ability of the weight strap to be tightend while the sensors are in position can ensure proper skin contact during testing. The sensors measure skin conductance to monitor the galvanic skin response of the body and heartrate measures like HR and the intervals between heartrate. The wires of the sensors go to a 3D printed electrical case housing the supporting hardware like the microcontroller and the battery. This box is hold by the user during testing.

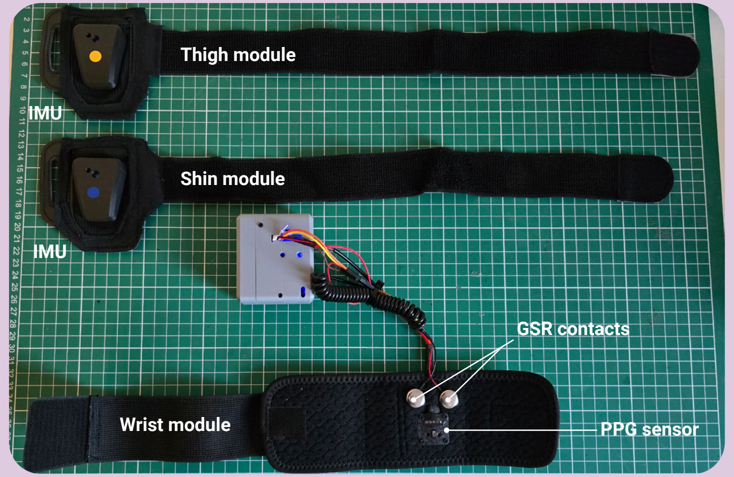


Figure 31: Overview hardware of the functional prototype


Figure 32: Person wearing the functional prototype

Figure 33: PPG holder assembly placed in The wriststrap

Figure 34: IMU case's assembly

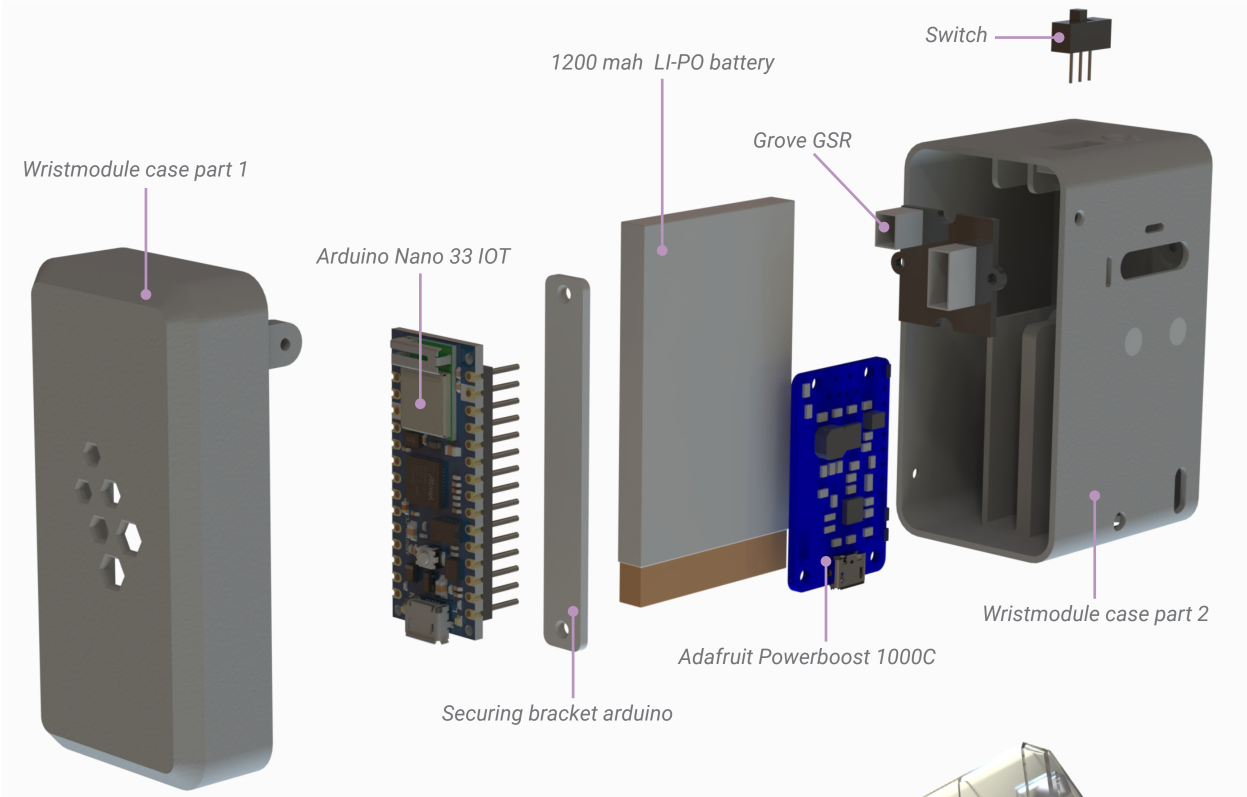


Figure 35: Exploded view Wristmodule box

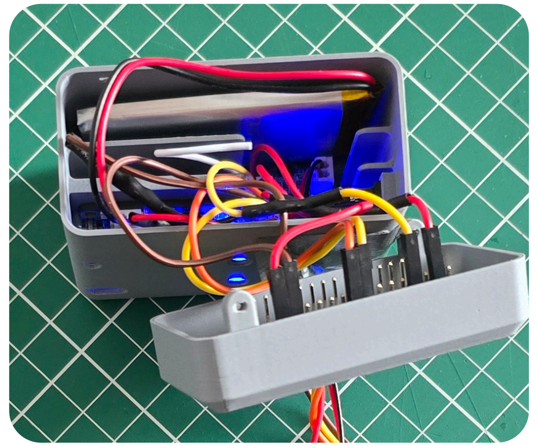


Figure 36: Wiring of theWristmodule electronic box

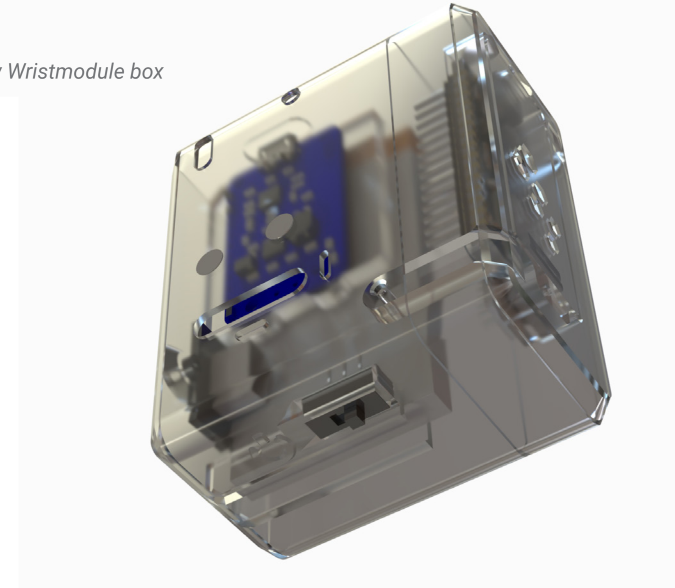


Figure 37: Transparent plastic render (visable component placement)

Software

The software needs to be able to collect the data from the sensors, compute the relevant metrics, record metrics and it needs to be easy to control during the user test. The IMU modules already have software of Witmotion and they provided the BLE protocol (Bluetooth 5.0 Communication Protocol | WITMOTION SDK, 2025)
to get the data from the sensors. The wrist module has to be programmed manually. To realize this a software package was created consisting of 3 scripts:

- **Symphysis_WristModule.ino (C++)**
- **Symphysis_Backend_Script.py (Python)**
- **Symphysis_Frontend_Script.py (Python)**

Symphysis wrist module script

This Arduino program is uploaded to the Arduino nano IOT 33 microcontroller. For this program a custom BLE protocol was created to transmit the data from the PPG and GSR sensor to the Symphysis Backend script.
The GY-MAX30102 (PPG sensor) breakout board is connected to the I2C (inter- integrated circuit protocol) communication pins. This protocol uses two wires consisting of SCL (clock) and SDA (data) lines allowing efficient data exchange while minimizing wiring complexity.
The captured infrared (IR) signals from the blood flow variations using the PPG sensor are analyzed to detect heartbeats. The detected heartbeats are used to get the heartrate in BPM as well as the RR interval between the heartbeats (time between successive heartbeats). This is done on the microcontroller because of latency.
The GSR value is measured on an analog pin of the microcontroller in a 12-bit format (0-4095). This value can be used to calculate skin conductance, which correlates with physiological arousal.
The metrics of the GSR sensor and PPG sensor are combined in the following data string:

Heartrate (BPM), RR interval (ms), GSR (analog(ACD)), IRvalue

This string is continuously transmitted to the backend script using the BLE service and characteristic at 200 hertz allowing for real time physiological monitoring.

Symphysis backend script

In the Symphysis backend script, all the functional parts of the system are built, from collecting data from the sensors and performing calculations to the recording of the data. This script will run on a supporting laptop.

First the backend script sets up Bluetooth Low Energy (BLE) communication with the three modules. This function uses the MAC addresses and characteristic, service and writing UUID's (Universally unique identifier) to connect to modules and open the communication channels. The script waits until all modules are connected before processing and keeps track of the module connection status in a separate function.

Once connected the script configures and calibrates the IMU modules by sending a calibration command and setting the output rate to 200 hertz to match wrist module data input. The IMU modules use advanced dynamics calculations and Kalman dynamic filtering algorithms to determine real time motion with a measured accuracy of 0.2 degrees (WT9011DCL 9-axis BLE Magnetometer Gyroscope, 2025). Furthermore, these sensors have a sensor fusion algorithm to compensate for drift by using the magnetometer.

The backend script gets the quaternion data from these sensors. A Quaternion is a four-dimensional vector used to describe rotation in 3D space. It consists 4 values (w, x, y, z) where "w" is the scalar component and "x,y,z" form the vector (imaginary) part.
Quaternions have the benefit of avoiding gimble lock, a phenomenon associated with Euler angles where discontinuities and singularities appear because of subtracting angles from each other.
The backend script formats a quaternion vector for the shin and the thigh. After that it produces the knee quaternion by using conjugate quaternion multiplication.

Q_knee=Q_thigh*Q_shin_conjugate

This function calculates the relative orientation of the shin compared to the thigh. After this calculation the script converts the quaternions back to Euler angles (degrees), which are easier to read using the following formula's:

roll=atan2(2(wx+yz),1−2(x2+y2))
pitch=asin(2(wy−zx))
yaw=atan2(2(wz+xy),1−2(y2+z2))

In this case roll, pitch and yaw represent the knee angles (flexion/extension, internal/external rotation, abduction/adduction) allowing the backend script to monitor the knee position in real time.
The data string that is coming in from the wrist module is decoded. The GSR value from the data string is used to calculate the Skin conductance. The calculation is based on a voltage divider equation. It translates the analog (ACD) signal into resistance values which are used to compute the skin conductance in micro siemens (uS).
Lastly, the backend script does a data processing loop where it continuously checks for incoming data from the three modules, calculates the values explained above, and queues the results for displaying the numbers in the frontend script seen next section. The final data stream that is produced at a frequency of 200 hertz is, see next page:

(Timestamp, knee flexion, internal/external rotation, HR, R-R interval, and skin conductance)

In this processing loop a recording function is build in. if the function "start recording" is called the data stream is written to a CSV (comma separated values) file. If the function "stop recording" is called the recording is stopped and the CSV file is saved to a folder on the computer. This file can be used for further analysis.

Symphysis frontend script

The frontend script is a GUI (graphical user interface) for the Symphysis wearable system, build using the Tkinter python library, see figure 38. It connects to the backend script and displays real time data, module connection status and the record button.
The interface uses images as indicators for the module connection status. If a module is connected the image is updated. This is built in for all three modules.
Under the connection status images the data stream is displayed in real time showing the live sensor data.
It also includes a record button, which allows the researcher to start and stop recording by clicking on the button. The backend script runs in a separate thread to prevent UI freezing while handling data streams and Bluetooth Low Energy (BLE) connections. Data from the backend is fetched using a queue, ensuring smooth real-time updates in the interface. The script runs an event loop, maintaining communication with the backend while keeping the UI responsive.
This user interface allows the researcher to monitor and control the system during testing.

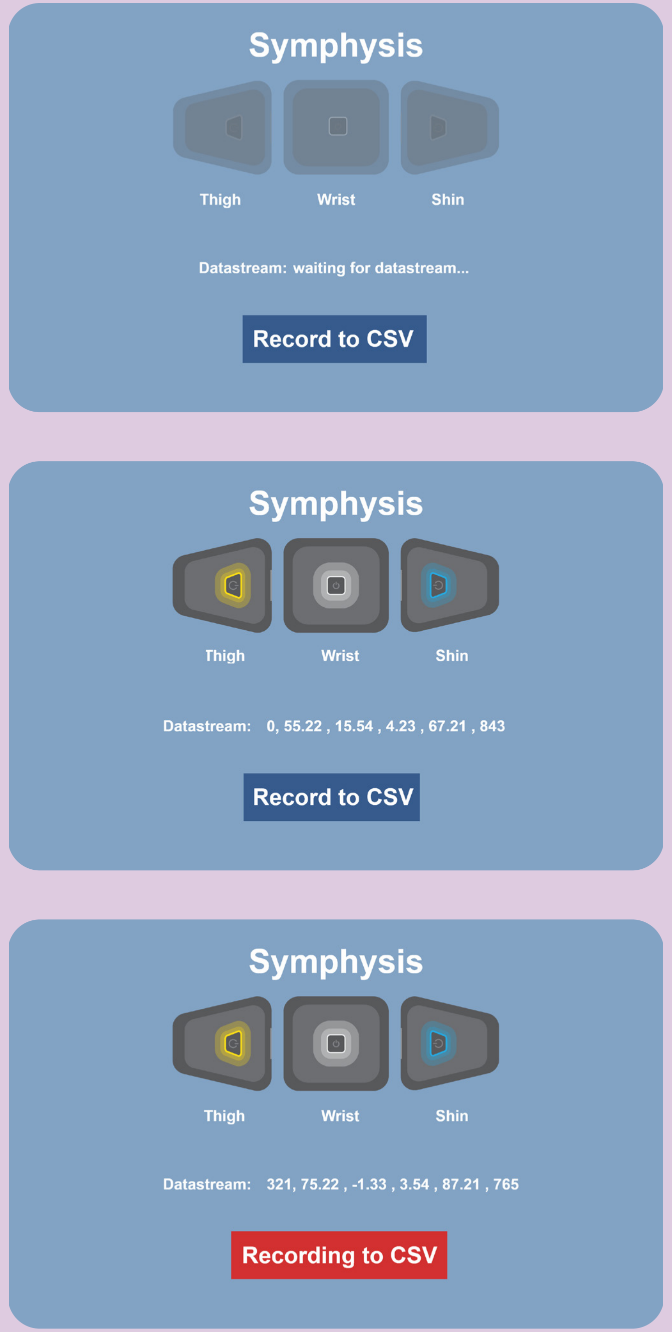


Figure 38: GUI generated by the Symphysis frontend script

4.2. Technical testing

In this section a brief technical test of the symphyis prototype is conducted to test the accuracy of the software and hardware combination created in section 4.1. These test incoperate evaluating movement data and heart rate messures.

IMU angle accuracy validation

In order to test the accuracy of the knee angles computed by the prototype a 90 degree angle was simulated using a large geometry triangle, see figure 38, in 3 different positions to see if their are inconsistencies in different positions of the knee:

1. The first position is 90 degrees with the bottom of the foot facing the ground
2. The second position is laying on the back and making a 90 degree angle with the knee
3. The third position is laying on sideways making a 90 degree angle

For each of these situations ten messurements each 5 seconds were taken from the system and a visual while keeping the 90 degree angle. the average was taken for each of the messurement see table 9.

position 1	position 2	position 3
90.2	89.3	89.4
90.6	90.2	90.0
89.4	90.1	90.4
89.9	90.3	90.1
90.2	89.4	90.3
89.9	89.6	89.9
90.4	90.0	90.5
90.7	90.1	90.0
90.2	90.4	89.6
89.5	89.3	89.3

Table 9: measurements with the system on the body

These tests show that the system accuratly detects knee angles with an accuracy of ~ 1 degree. however these messurement maybe influenced by movement therefore extra testing without the sensor straps have been conducted concluding an accuracy of ~0.6 degree, see figure 39. This is less then the sensor accuracy of 0.2 degrees.

Figure 38: position 1 of the messurements on the body

Figure 39: messurements witout the straps (position 3)

Smartwatch comparison

The Symphysis functional prototype uses heart rate measurements, such as BPM (beats per minute) and HRV (heart rate variability), to monitor changes in the nervous system. To evaluate the accuracy of the Symphysis prototype in producing these metrics, a small comparison test was conducted using an Apple smartwatch.

For five intervals, each lasting one minute, the average heart rate and SDNN (standard deviation of NN intervals) were recorded from both the smartwatch and the Symphysis prototype. See Table 10, 11 for the results.

Apple smartwatch (1-min avg BPM)	Symphysis PPG sensor (1-min avg BPM)
85	83
84	87
86	80
87	87
85	90

Table 10: 5 x 1-minute test of average BPM

The results show that the Symphysis system has a maximum difference of 7 BPM compared to the smartwatch measurements. However, while the smartwatch maintained more stable values around the average heart rate, the Symphysis system occasionally displayed greater fluctuations in BPM. This led to higher HRV values, specifically SDNN, in the Symphysis system compared to the smartwatch, as shown in Table 11. These differences may indicate a need for additional filtering or smoothing of the PPG sensor signal in the Symphysis system.

Apple smartwatch (1-min SDNN (ms))	Symphysis PPG sensor (1-min avg SDNN (ms))
44	60
42	65
44	54
44	48
44	65

Table 11: 5 x 1-minute test SDNN (HRV)

In conclusion, the Symphysis system is capable of detecting movement with an accuracy of approximately 0.6 to 1 degree. Regarding heart rate measurements, the Symphysis prototype can accurately detect BPM and provide reliable average values. However, HRV measurements still show higher fluctuations in the sensor data. To improve the accuracy of HRV readings, implementing outlier detection or applying a moving average filter could be beneficial. Validation of the GSR sensor has not been done against a certified device, for further development this is recommended.

Figure 40: Smartwatch VS Symphysis prototype

4.3. Usertesting

Introduction

The concept of the wearable symphysis described in chapter 3 requires validation of its capabilities. Therefore, a user test needs to be conducted to see if the concept of the system is feasible and how users experience the design. The goal of this research study is to evaluate whether Symphysis is intuitive to use, whether it can accurately detect these emotional signals and whether the results are promising for further clinical research. The data collected during this study will be anonymized and deleted after the study is complete. The ethical approval of this study was conducted by HREC, the ethical commission of the technical university of Delft, and can be found in appendix O.

1. **To validate whether Symphysis can effectively track stress responses and knee movement.**
2. **To determine correlations between stress signals and movement metrics under different conditions and participant perceptions.**
3. **To evaluate the usability, comfort, and engagement of the system based on participant feedback.**

Methods

Previous studies, such as those by He et al. (2024), have demonstrated that adding a cognitive load can influence physiological responses related to emotional arousal. Building on this, this study involves a healthy participant performing squats both with and without an additional cognitive load while wearing the Symphysis system. Before the test, a 5-minute baseline measurement is taken to establish the participant emotional arousal levels without any external commands. After completing the tasks, participants are asked to fill out a questionnaire to share their perceptions of the experience, the movements, the emotional intensity of the tasks, and the usability of the wearable.
The data collected from the three tests (baseline, movement without cognitive load, and movement with cognitive load) are compared to each other and to the participant's self-reported perceptions in the questionnaire. This comparison aims to verify whether Symphysis can detect the added cognitive load through its sensors, whether the participant's perceived increase in emotional intensity aligns with the system's measurements, how the wearable prototype system's usability is perceived.

Participant selection

In this study 5-10 participants were asked to join this study. In this study "healthy" participants are selected. It is still unknown if symphysis is working reliably so no intervention in rehabilitation programs can be made ethically. Furthermore, the participants will stay anonymous during the study. The requirements for a participant are the following:

- The participant must be in the age range from 18-65
- The participant has no severe injuries or surgeries that could hinder the procedure
- The participant needs to be mentally and physically capable to perform squats.
- The patient has no allergic reactions to wearable materials

Materials

Setting

the study will be conducted in a dedicated controlled environment, because outside factors could influence the results. A plan of the test setup can be found in figure 41.

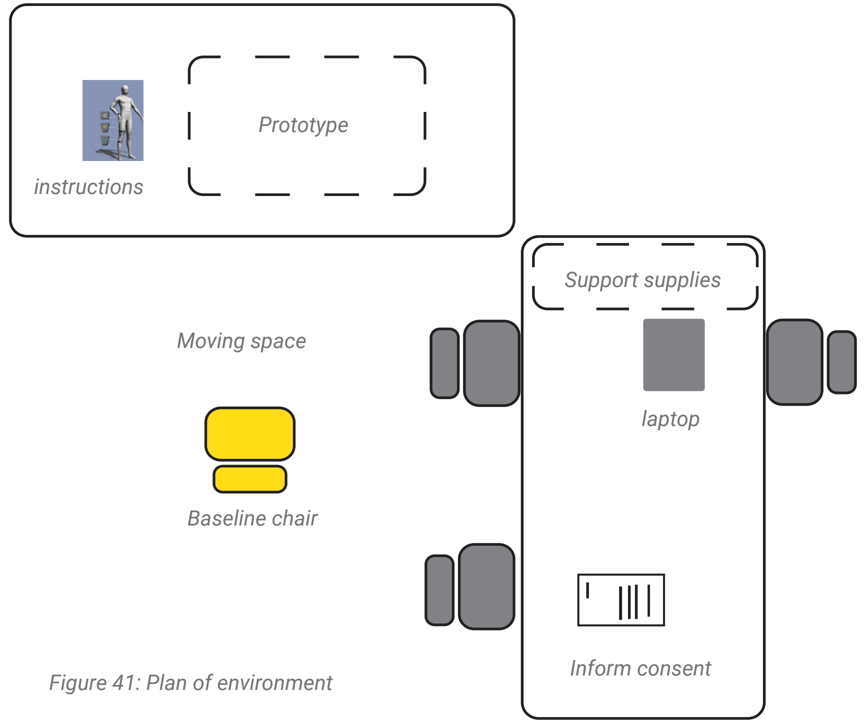
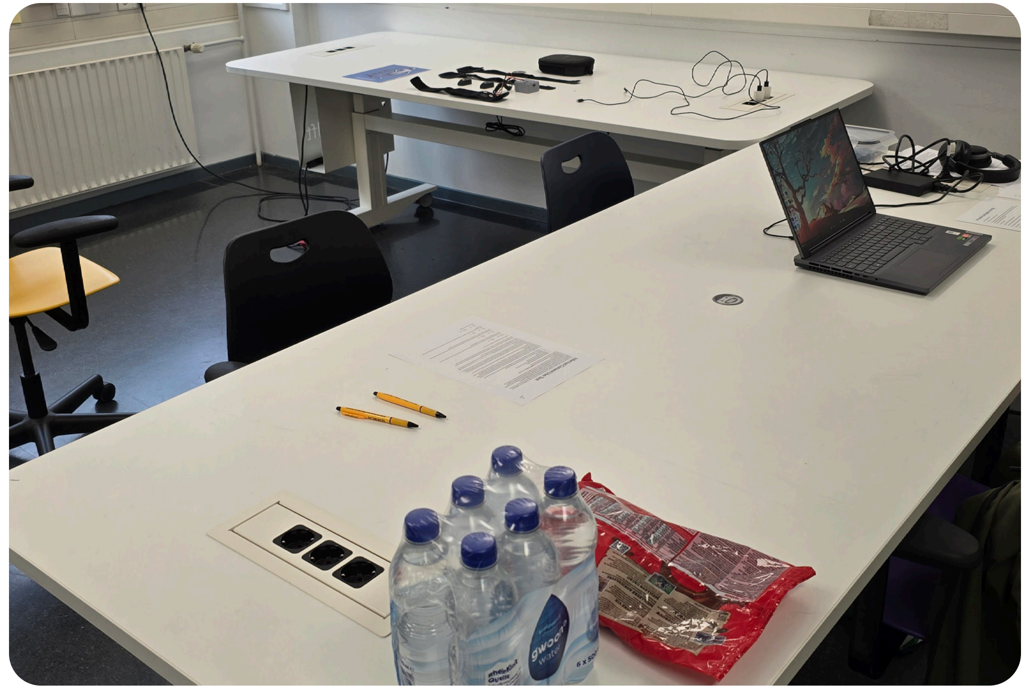


Figure 41: Plan of environment



Symphysis functional prototype

For this user test a wearable prototype was created. This wearable consists of the 3 modules explained in the concepts. The modules communicate by Bluetooth to a python software package created for this test. The sensors and program are able to collect the sensor data at 200 hz and safe it to a CSV file. For more detailed information about the prototype see 4.1. The data stream that is produced is:

(Timestamp, flexion/extension, Internal/external rotation, Skin conductance, Heartrate, intervals between heartbeats)

Data analysis Script

The user test produced long CSV files that could be best analyzed using python. Therefore, a data analysis script was created to automatically produce the relevant graphs and a report of the metrics and statistics of the user test. The data analyses procedure is described in the data analysis section of the method.

Other materials

- Inform consent forms on paper
- A working pen
- Laptop (with prototype software)
- Questionnaire
- QR code to questionnaire
- Disinfecting spray
- Instructions of putting on the sensor

Procedure

The study contains 3 parts: The pre-test part, the user test and the post-test phase. In this section the procedures of each phase is explained.

Pre-test:

Before testing the participants were informed about the purpose of this study and need to sign an inform consent, see appendix V. If the participant met the requirements for participation, the participant will be assigned a participant number.

Test:

The participant used the instructions provided to put on the symphysis wearable prototype on the right leg. During this the researcher assisted where necessary. After that the participant sat down to start the measurements. For each participant three mesurements are taken.

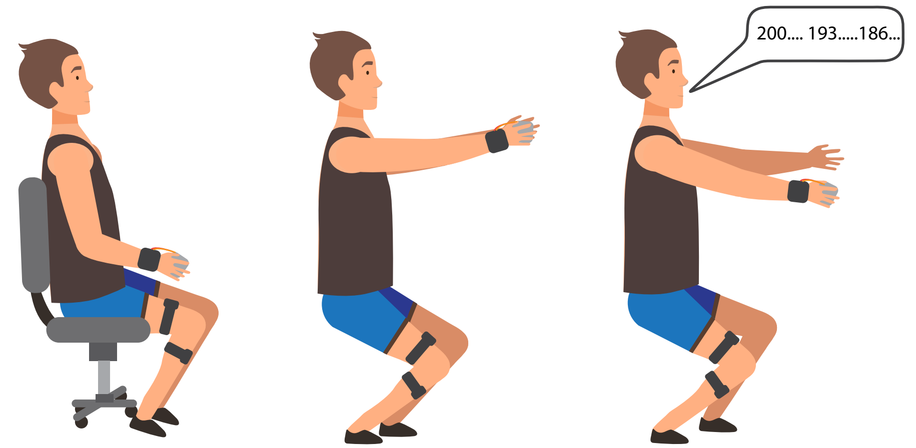
1. Baseline: participant sit comfortable with the sensors running for 5 minutes to get a baseline measurement related to emotional arousal (HR, HRV and skin conductance). This baseline was determined looking at literature. Skin conductance (SC) is sensitive to rapid changes in emotional states. a 2–5-minute baseline is sufficient to capture stable levels (Boucsein, 2012; Dawson et al., 2017). Heart rate (HR) and heart rate variability (HRV) requires a longer baseline ranging from 3-10 minutes for heart rate (Berntson et al., 1997; Laborde et al., 2017) and 5-10 minutes for heart rate variability (HRV) (Task Force of the European Society of Cardiology, 1996; Shaffer & Ginsberg, 2017). 5 minutes was chosen to minimize patient fatigue and get an accurate foundation baseline for this study.

2. Neutral condition: The participant will perform 15 body weight squats wearing the symphysis system prototype.

In between these test a rest period of 2 min is taken.

3. Cognitive Load Condition: Participants perform the same 15 squats while doing a cognitive load task. The cognitive task given is counting backwards in steps of 7 starting at 200. Counting backwarts in steps of 7 is a known method to trigger the sympathetic nervous system response, because of the cognitive load (Castro et al., 2009). Dual-task scenarios like counting backwards during exercise has shown that increased cognitive load can affect physiological responses. These responses can alter gait patterns and influence stress related mesures (Baek et al., 2021).

During the test phase the stress metrics and movement data during each task are recorded to a CSV file named: SensorData_Participant_N_test_N. These files were stored in a folder dedicated to the participant.



Test 1: baseline *Test 2: Exercise* *Test 3: Exercise with cognitive load*

Post test:

The participant can take off the symphysis wearable prototype then participants answer questions about the test in an online survey (usability, comfort, user interface design, how they perceive emotional and how intense they felt the emotion). The questions in this survey can be found in appendix X.
Demographic factors such as age, gender, fitness level, and stress resilience are collected to assess their potential influence on range of motion (ROM), speed, and physiological responses. Additionally, participants are asked about their perception of emotional intensity during the tests and any differences they experienced, providing insight into how they perceived the assessment. Lastly, questions regarding the intuitiveness and comfort of the wearable system are included as well as intrepretations of the overview metrics . Responses are recorded using a 7-point Likert scale.
After that the participant will be thanked for their participation. Then the prototype will be checked for defects and disinfected for the next participant.

Data analysis

Sensor data analysis

For analyzing the sensor data from the wearable system the python script is structured to perform multiple analytical steps. First, it loads the recorded CSV files, organizes them per participant and test, and extracts the metrics of the data stream. Using these metrics the script computes the extremes and averages of the values, the HRV metrics (RMSSD and SDNN), Angular velocity, angular acceleration and angular jerk.
Before angular velocity, angular acceleration and angular jerk was computed a Butterworth filter was applied on the position data to reduce noise that could lead to large spikes in the velocity and acceleration because of the small timesteps in the differentiation process.
Unlike other filters that can introduce ripples or distortions, the Butterworth filter preserves the shape of the original signal while effectively reducing high-frequency noise.
In adition to the metrics a five by two plot grid was generated, visualizing the data over time
After that the script conducts a paired-sample T-test between the metrics of test 2 and test 3 to see the significance of changes in physiological and biomechanical metrics due to the added cognitive load. The P value for significands will be P=<0.05.
Furthermore a Cohen's d (Bhandari, 2022) is introduce to judge the effect size of the difference between the metrics:

Cohens d = Mean difference between (test 3 - test 2)/ standard deviation (test 2)

d < 0.2 = very small effect
0.2 < d < 0.5 = small effect
0.5 < d < 0.8 = medium effect
d > 0.8 = large effect

The script generates graphs of biomechanical movement over time across the different tests to visualize movement patterns and changes in psychological values. Furthermore, it generates a report of the metrics per participant and the statistical analysis.

Questionaire data analysis

To analyze the questionnaire data collected following the Symphysis wearable system user test, both quantitative and qualitative methods will be employed. Quantitative responses from Likert-scale items across the four sections: demographics, test perceptions, usability and understanding of metrics, will be analyzed using descriptive statistics, like means of data collected, to assess variability in user responses. Correlations may also be calculated to investigate relationships between perceived usability, emotional intensity, and understanding of metrics.

Qualitative responses, such as descriptions of emotional experience and feedback on the overview metric presentation concept, will be analyzed to identify recurring patterns and user intrepretation of the overview metric. This approach enables an evaluation of user perceptions, emotional impact, system usability, and the clarity and relevance of presented physiological metrics in the context of knee rehabilitation.

Hypothesis

For this study is expected that the cognitive load in addition to the physical exercise will trigger a response from the autonomic nervous system affecting physiological mesures like skin conductance, HR, HRV and less smooth and consistent movement.

Results

A total of nine participants took part in the user test. This section presents the results of the sensor data, questionnaire responses, and the combined analysis of both.

Sensordata

Sensor data was collected and analysed for each participant, resulting in ten graphs and one metrics table per participant that illustrated performance outcomes. These visuals are included in Appendix Y.

Technical findings

The user test took place at the Technical University of Delft. The environment presented several technical challenges due to the high density of Bluetooth devices, which occasionally interfered with the connection to the modules. In addition, the PPG sensor did not perform optimally during the usertest, showing increased noise levels and skipped beats. The specific cause of this issue remains unknown, but the issue increased with extra movement.

Another notable issue was the placement of the wrist module prototype. Achieving consistent skin contact proved difficult for some participants, while for others the placement was straightforward. The reliability of the sensor readings was dependent on this contact. A visual representation of this issue can be found in Figure 42.

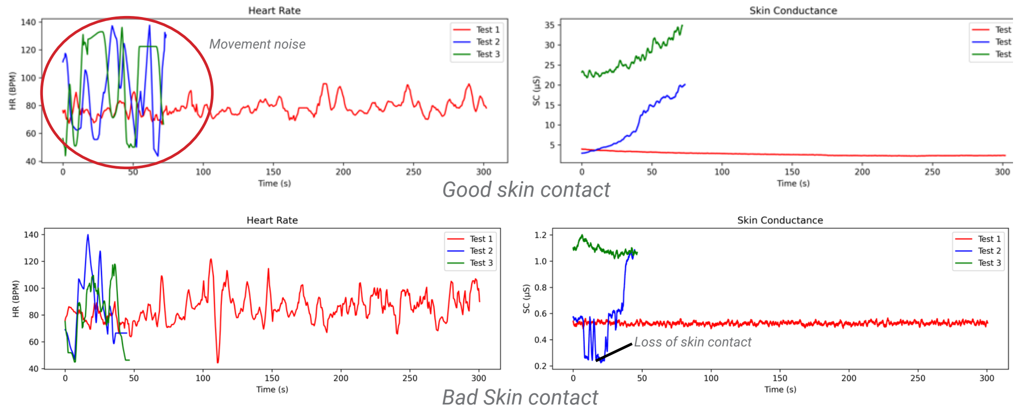


Figure 43: Technical challenges with skin contact and sensor noise

Baseline Measures

During baseline measurement, individual differences between participants became apparent. Skin conductance values ranged from 0.53 to 5.17 micro siemens. According to Doberenz et al. (2011), a healthy baseline (in rest state) lies between 2 and 20 micro siemens. Four out of nine participants had baseline values below 2 micro siemens.

Average heart rate during the 5-minute baseline ranged from 64 to 85 beats per minute (BPM). Heart rate variability (HRV), measured through RMSSD and SDNN, occasionally showed incorrect values and thus cannot be reliably used for drawing conclusions in this study.

Paired sample T-test: comparison of test 2 and test 3

Table 12 presents the results of the paired sample T-test comparing test 2 (physical task only) with test 3 (physical task combined with cognitive task). A significant difference is indicated by a P-value less than 0.05, shown in green. Effect sizes are denoted with a plus or minus sign, with the plus indicating an increase in test 3 compared to test 2, and the minus indicating a decrease.

Participants took significantly longer to complete test 3 compared to test 2 (P = 0.021, d = 0.96). Average skin conductance was also significantly higher in test 3 (P = 0.038, d = 0.83). Additionally, maximum internal rotation velocity was higher in test 3 (P = 0.045, d = 0.28), and maximum range of motion in internal and external rotation was also greater (P = 0.049, d = 0.17). Other metrics presented in Table 12 did not show significant differences.

Statistical Analysis (Test 2 vs Test 3)

Metric	p-value	Effect Size
Time (s)	p = 0.021	+0.96
Avg SC (μS)	p = 0.038	+0.83
Max Velocity Rotation (deg/s)	p = 0.045	+0.28
Max Internal/External Rotation (deg)	p = 0.049	+0.17
Avg Velocity Flexion (deg/s)	p = 0.083	-0.49
Max SC (μS)	p = 0.094	+0.68
Min SC (μS)	p = 0.130	+0.75
Avg Jerk Rotation (deg/s³)	p = 0.197	-0.34
Avg Velocity Rotation (deg/s)	p = 0.267	+0.11
Min Flexion/Extention (deg)	p = 0.291	-0.27
Max Flexion/Extention (deg)	p = 0.514	-0.10
Min HR (BPM)	p = 0.533	+0.26
Avg Jerk Flexion (deg/s³)	p = 0.551	-0.23
HRV RMSDD (ms)	p = 0.564	+0.15
Min Internal/External Rotation (deg)	p = 0.607	-0.09
Max Acceleration Rotation (deg/s²)	p = 0.645	+0.07
Max Jerk Rotation (deg/s³)	p = 0.673	+0.11
Max Velocity Flexion (deg/s)	p = 0.688	-0.09
Avg HR (BPM)	p = 0.714	+0.14
Max Acceleration Flexion (deg/s²)	p = 0.720	+0.09
Avg Acceleration Flexion (deg/s²)	p = 0.773	+0.13
Avg Acceleration Rotation (deg/s²)	p = 0.795	+0.11
Max Jerk Flexion (deg/s³)	p = 0.840	-0.09
HRV SDNN (ms)	p = 0.866	+0.07
Max HR (BPM)	p = 0.881	+0.08

Table 12: Statistical Analysis usertest

Effects of the Cognitive Task on Movement Data

Analysis of the movement graphs revealed several consistent patterns. In knee flexion and extension jerk, the impact of the cognitive task was less evident. However, pauses in movement were more frequent during test 3 (see Figure 44, with test 3 represented by the green line and test 2 by the blue line).

Larger spikes were observed in the internal and external rotation graphs during test 3, which may reflect greater variability in movement under cognitive load (Figure 46). In some cases, the sensor shifted slightly during the test, which was most apparent in the internal/external rotation data at the beginning of the graphs, see figure 45.

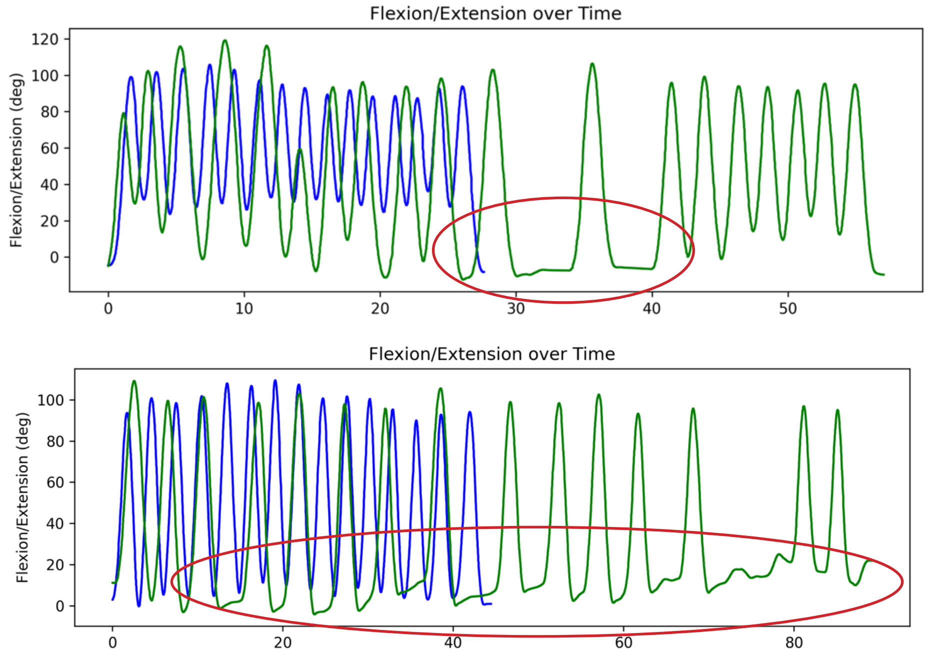


Figure 44: Examples of pauses in test 3 (participant 7 & 9)

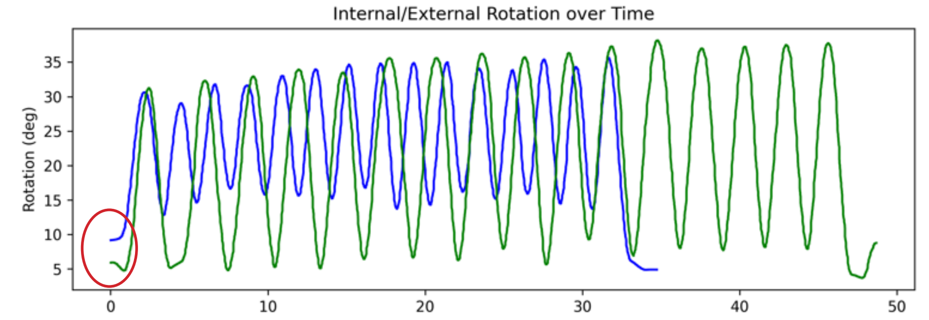


Figure 45: Example sensor shift during usertesting

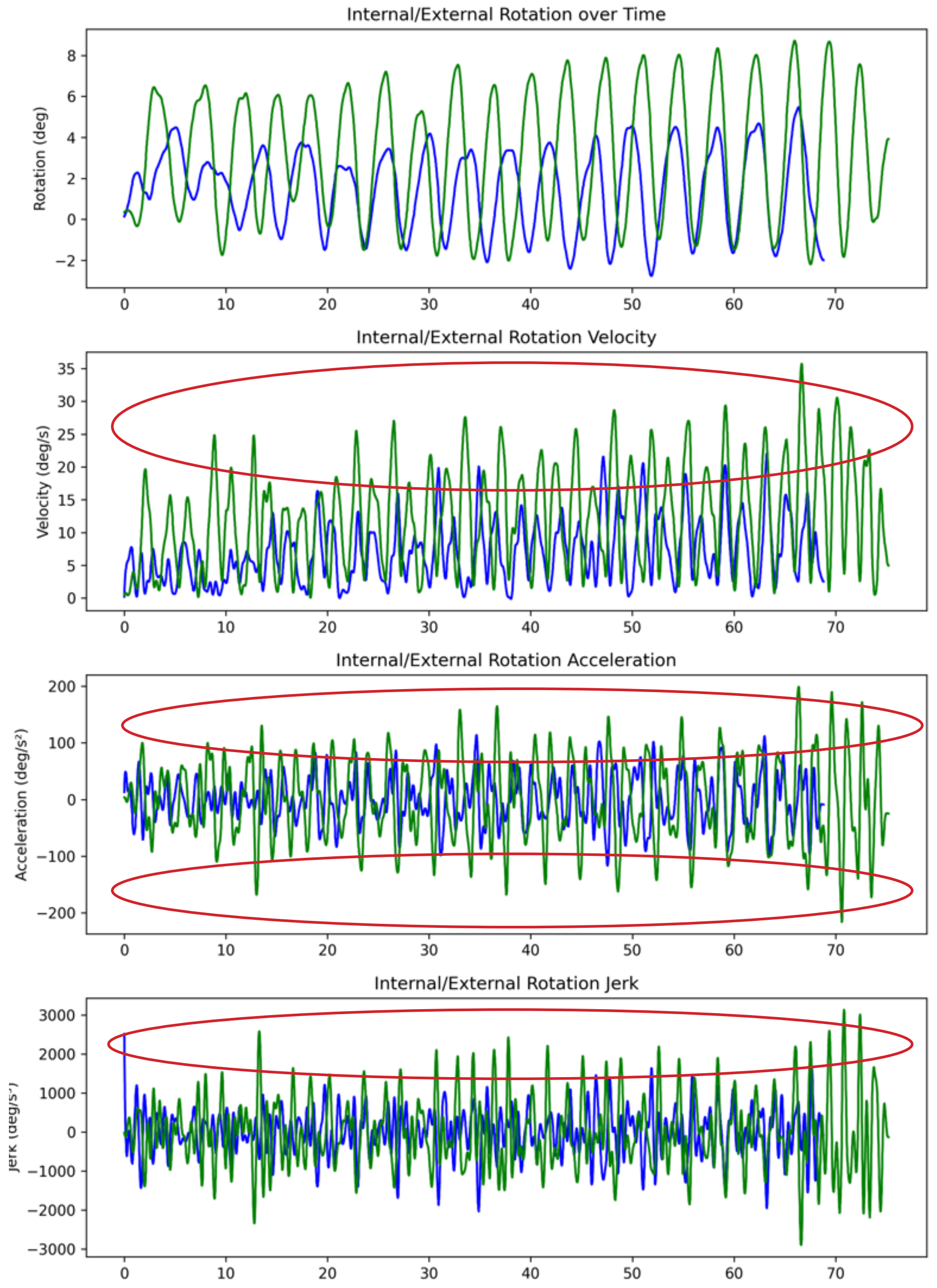


Figure 46: Example of the increase in spikes in jerk and velocity of internal and external rotation of the knee

Relationship Between Movement and Skin Conductance

Although a comprehensive correlation analysis is outside the scope of this results section, preliminary observations suggest that increased skin conductance during test 3 aligns with changes in movement variability. This suggests a possible link between cognitive stress and motor control that warrants further investigation.

Questionnaire results

In this section the result of the questionaire are described. For all the awsers of the questionair see appendix Z.

Demographics

The study involved nine participants. The average perceived fitness level was 3.8 out of 7 on a Likert scale. Six participants were in their twenties, while the remaining three were aged 34, 44, and 64, resulting in a mean age of 32, indicative of a relatively young sample group.
Perceived stress susceptibility varied, ranging from 2 to 5 out of 7 (average: 3.7). Similarly, the self-reported ability to count backwards ranged from 2 to 6. Participants rated the squat exercise as moderately challenging, with an average difficulty rating of 3.3 out of 7.

Perception of the tests

Emotional intensity during squats without the cognitive task was rated as 2.7 out of 7 on average. When the cognitive task (counting backwards in steps of 7) was added, emotional intensity rose to 4.6 out of 7.
Five participants explicitly mentioned experiencing stress. Other themes included difficulty focusing on two tasks simultaneously and pressure to correctly perform the number sequence. Most participants found test 3 more mentally challenging, although one participant reported experiencing less physical strain due to being distracted by the mental task. Participants perceived that the cognitive task influenced their physical movement, giving an average rating of 5.8 out of 7. Balance was also noted as more difficult during this test.

Intuitiveness and comfort

Participants found the instructions for sensor placement intuitive, with a rating of 6.3 out of 7. Most were able to place the system correctly without assistance, except for the wrist module prototype, which required support. Overall, the comfort of the system was rated positively at 5.5 out of 7. However, the wrist module was criticized for being tight and bulky.

Interpretation of the Data Overview

When asked to interpret the data overview, see figure 47, without prior explanation, three participants mentioned the visual cue of filling circles. Three participants also assumed that red colouring indicated that a knee strain value was problematic and needed to be addressed. Seven participants mentioned aspects related to relaxation, recovery, or emotional regulation. After receiving the explanation of the data overview, seven participants reported that they understood it clearly, and their interpretation improved accordingly.

Understanding of Metrics

Five participants had heard of HRV before. The in-app description of HRV was rated as 5.8 out of 7 for clarity. Only three participants were familiar with skin conductance (SC), but the SC description received a clarity rating of 6.1 out of 7. The term "jerk" was known to just two participants, and its explanation scored 5.2. Four participants were familiar with range of motion (ROM), with the explanation receiving the highest clarity rating of 6.4 out of 7.

Figure 47: Data overview that was interpreted in the questionnaire.

Participant specific relations

Below, the results per participant are discussed in detail, focusing on movement data, emotional responses, and subjective experience during the tests and how these relate.

Particpant 1

Participant 1 has a low fitness level and experiences stress quite quickly but does not really struggle with counting backwards. Movement during test 2 and test 3 was very similar in flexion and extension. Internal and external rotation showed an increase in movement speed and jerk. Interestingly, participant 1 described the emotion in test 3 as: "I think the stress was to find a balance between the two tasks. I think I eventually found a balance by focusing on the counting and doing the squats more on autopilot." Skin conductance was initially higher but decreased over time. Furthermore, the movement data became more consistent and faster throughout the test.

Particpant 2

Participant 2 has a high fitness level, experiences stress neutrally, but finds counting backwards harder. In test 2, participant 2 performed very explosive squat movements with a high range of motion in flexion and extension, from -4 to 115 degrees. In test 3, the range of motion was similar but movement was about 30% less explosive when looking at maximum flexion/extension acceleration. The participant described their experience in test 3 as: "I felt a bit stressed out in the last test because I could not really keep a good rhythm in my movement. Also, a bit of frustration because I could not get my movement as great in the last test." The skin conductance showed a steady increase during test 3.

Particpant 3

Participant 3 has a low to moderate fitness level (3/7), experiences stress relatively quickly (5/7), and is moderately skilled at counting backwards. The participant stated: "It was quite stressful. I felt as though I were constantly in a rush. There was a certain pressure to perform, which left me feeling frustrated when I couldn't think of the correct number. During the first exercise, I felt more confident and in control." Skin conductance showed a high spike towards the end of test 3. Movement data between test 2 and test 3 did not show large differences, although in test 3 there was higher jerk in both flexion and extension as well as in internal/external rotation.

Particpant 4

Participant 4 has a low fitness level, experiences stress quite quickly, but does not struggle much with counting backwards. Movement data showed a significant increase in jerk in test 3 in both flexion and extension, as well as in internal and external rotation. Movement was less consistent compared to test 2. Skin conductance during test 3 showed a decreasing trend with a sudden drop to zero, suggesting a possible malfunction in the sensor contact. The participant described their experience in test 3 as: "I felt quite stressed. I tried to keep the movement going while counting, but multitasking is not exactly my strength, and maintaining my balance became more challenging."

Particpant 5

Participant 5 has a relatively high fitness level, does not experience stress very quickly, but finds counting backwards quite hard. The movement data showed a significant increase in jerk during test 3 for both flexion/extension and internal/external rotation, with larger spikes observed. Skin conductance showed a stronger emotional response in test 3 compared to test 2, with a rising trend and a large increase halfway through the test. The participant stated: "It was more challenging than I expected, and I found myself feeling a bit unfocused. As time went on, the frustration started to build."

Particpant 6

Participant 6 has a relatively high fitness level, does not usually experience stress quickly, and does not find counting backwards very difficult. Movement data showed little effect from the cognitive task, aside from a longer completion time in test 3. Skin conductance was higher but showed no large spikes, indicating no strong emotional fluctuations. The participant described their experience as: "I didn't feel much of a difference, but staying consistent was definitely more difficult. I was curious to figure out how to perform both tasks at the same time, and I found it quite challenging." This suggests that the participant approached the cognitive load more as a challenge rather than experiencing it as stress.

Particpant 7

Participant 7 has a high fitness level, experiences stress moderately fast, and finds counting backwards relatively hard. Movement data showed less consistency during test 3, with noticeable pauses at the top of squats and more variation in the range of motion. Squats during test 3 were less explosive. About halfway through the 15 squats, large pauses were followed by more consistent movement, coinciding with increased spikes in skin conductance. The participant described their emotional experience as: "Stress, doubt if I got the number sequence right."

Particpant 8

Participant 8 has a low fitness level, does not experience stress very fast, and finds counting backwards relatively hard. Movement data showed no major difference between test 2 and test 3, except that the duration of the squat set was longer in test 3. Interestingly, the movement was more consistent during test 3. Skin conductance showed a slight increase but no major emotional response. The participant described their experience as: "The extra task of focussing on the counting made me fully focus on that, which was interesting, because I experienced a lot less physical strain (mentally that is) than I did during the first set. The actual strain was about the same probably, but the counting greatly affected my interpretation."

Participant 9

Participant 9 has a low to moderate fitness level, does not experience stress very fast, and finds counting backwards moderately hard. Movement data showed significant sensor shift during internal and external rotation, meaning the sensor was not stationary. There were also many pauses at the top of the squats during test 3, and the movements were less explosive compared to test 2. Skin conductance showed a stronger emotional response during test 3, with large changes and a rising trend. The participant described their experience as: "Combining two tasks becomes increasingly difficult; at first you think about the squats, but later you focus more on the counting down."

Discussion

The user test aimed to investigate if the Symphysis prototype could detect physiological reactions to emotions related to knee movement. In this study the effect of a cognitive load on physical movement and emotional responses during a squat exercise was tested. The combination of the results sensor data of the Symphysis prototype and questionnaire results provided insights into the impact of the cognitive load on motor performance and physiological stress responses.

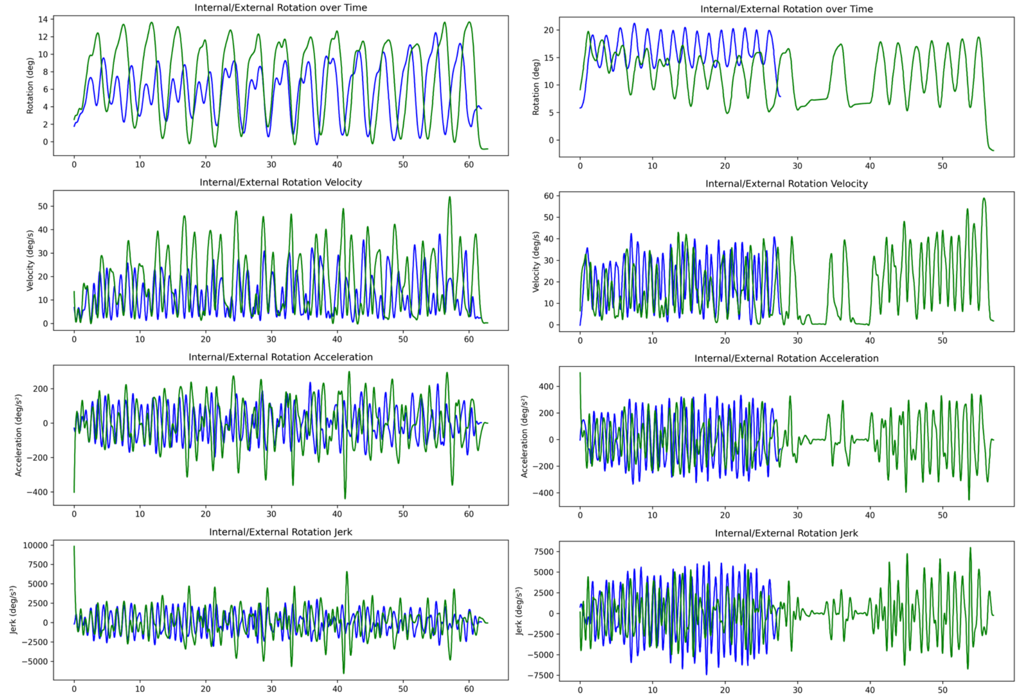
Wrist module issues

Several technical limitations of the wrist module affected the data collection process. The PPG sensor unfortunately produced too much noise, especially during the two tests involving movement (test 2 and test 3), making this data unusable for analysis. In addition, skin contact varied between participants, likely due to anatomical differences, dry skin, or sensor placement issues. Furthermore, participants suggested that this module was the least comfortable of the three modules. The strap was reported as being tight and bulky. These technical issues and the lack of comfort should be addressed in future iterations of the wrist module's design and technical function.

Impact of the cognitive load on performance

The paired sample T-test showed a significant large effect of time increase in test 3, indicating that participants took longer to complete the test with the added cognitive load. Although this shows that cognitive load impacted the time to complete repetitions, the difference in time also allowed for different adaptation strategies among participants. This made it harder to make accurate comparisons, especially in knee flexion and extension. Some participants slowed their movement by reducing explosiveness, others paused at the top to process the cognitive task before proceeding, and some fully embraced the challenge of performing both tasks simultaneously, see figure 48. Therefore, a guided exercise, such as following the pace of a video, is recommended for future studies to eliminate variability in adaptation strategies and enable easier comparisons.
Despite these differences in adaptation strategies, there was a small but significant effect on internal/external rotation ROM and velocity. This suggests that participants had to make larger and faster corrections in their knee movement, indicating that balancing was more challenging in Test 3, this effect is small but detected by the prototype. Interestingly, this effect was more visible in participants who completed test 2 and test 3 with minimal time differences (Participants 1, 3, 4, and 5). Figure 48 also shows this effect.

The increase in movement jerk and variability under cognitive load aligns with previous research indicating that divided attention negatively affects motor control (Friedman, 2007; (Baek et al., 2021)). However, the effects varied between participants: some showed clear declines in movement consistency and explosiveness, while others demonstrated either stable or even improved consistency during test 3, suggesting individual differences in resourcefulness when combining cognitive load and motor control.



Internal rotation participant 5: Strategy of doing the tasks at the same time .

Internal rotation participant 7: Strategy of taking more time and pause at the top in test 3

Figure 48: Example of different adaptation strategies of participants

Emotional and physiological responses

Skin conductance in test 3 was significantly higher compared to test 2, with a large effect size, showing a stronger physiological response during dual-task performance. However, skin conductance already started at a higher level for most participants, see figure 49, and the source of this is not entirely clear. The two-minute resting period may not have been sufficient to return skin conductance to baseline before beginning measurements again. Additionally, the response could have been triggered by participants receiving instructions for the cognitive task before test 3, causing a stress response before recording. Finding a way to eliminate this uncertainty in future studies would provide a more accurate representation of skin conductance changes between tests.

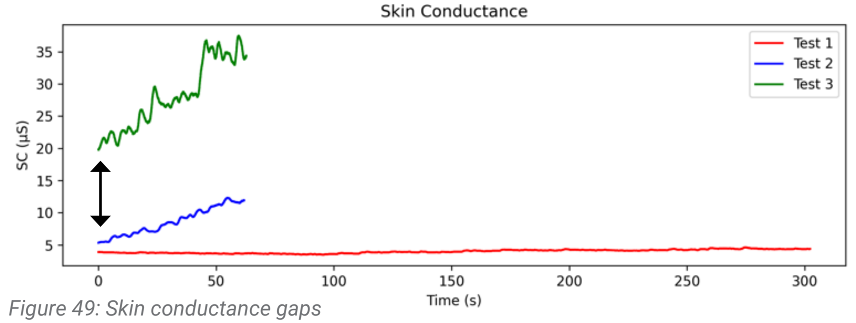


Figure 49: Skin conductance gaps

Relation between emotional arousal and motor control

The rise in skin conductance, increased movement inconsistency, and signs of instability in internal/external rotation measures hint at a potential link between emotional arousal and motor control under cognitive load. Questionnaire responses support these findings. Participants rated test 3 as more emotionally intense and challenging compared to test 2. Stress and frustration were common emotions during test 3, although some participants framed the cognitive challenge more positively, suggesting that the perception of the challenge plays a role in emotional responses and motor control.

Usability and system feedback clarity

Overall, participants found the system intuitive to use and comfortable to wear, with some criticisms directed at the wrist module, including the tight strap and bulkiness of the prototype. While most criticism came from it being an early prototype, balancing comfort with sensor contact remains a challenge.

The data overview presented to participants provided great insights into their perception of the metrics. However, the visual cue of filling circles was not interpreted as originally intended. Therefore, a different form factor for the overview is recommended. Additionally, color played a vital role in user perception: the color red was seen as indicating something bad, which was not the intended message. In future designs, colors that might suggest a good or bad state should be avoided.

Many participants originally suggested that the overview showed the emotional load they experienced and that they needed to focus more on recovery, which were correct interpretations. However, even after explanation, 2 out of 9 participants still did not fully understand the overview, indicating that a reformulation and redesign is needed.
The clarity of more detailed metric explanations in the app was rated highly, although technical terms like jerk remained less well understood. This suggests the need for simpler language or improved visual aids.

Limitations

This study was conducted in a controlled environment using healthy participants rather than patients undergoing knee rehabilitation due to ethical concerns. As a result, the data generated does not provide evidence of the system's effectiveness in real rehabilitation scenarios. Further testing with the target population is necessary to validate its clinical effectiveness. Additionally, the small sample size may have led to a lack of variance in the dataset, limiting the generalizability of the findings. Future studies with larger participant groups are required to ensure the reliability of the results.

The cognitive load induced in this study primarily reflects general stress rather than movement related fear or pain, which are critical factors in knee rehabilitation. Therefore, additional validation in real world conditions is needed to fully assess the system's effectiveness.
Furthermore, while the prototype was tested for accuracy, the extent of its accuracy remains uncertain, especially with the technical difficulties encountered during this user test. Comparing the system's performance with professionally validated measurement tools could provide a more precise evaluation of sensor data reliability.

Another limitation is the variability in participant's ability to perform the cognitive load task, counting backward in steps of seven. Differences in ability may have influenced task difficulty and, consequently, the results. Additionally, the study short testing duration may have affected the accuracy and representativeness of the physiological data. Longer observation periods could provide more reliable insights into the system performance.

Lastly, the questionnaire responses may have been influenced by subjective perception, recall bias, or social desirability bias potentially affecting the accuracy of the comparison between perceived and measured emotional intensity. Future studies should incorporate objective psychological or physiological measures to complement self reported data and enhance the reliability of findings.

Conclusion

The user testing of the Symphysis prototype demonstrated promising potential for detecting physiological and emotional responses to cognitive load during knee movement exercises. Although technical challenges, particularly with the wrist module's comfort and PPG sensor reliability, affected data quality, valuable insights were still gained. The study confirmed that added cognitive load significantly impacts motor performance, increasing movement variability, internal/external rotation instability, and physiological stress responses as indicated by elevated skin conductance levels.
Despite participant differences in adaptation strategies, consistent patterns suggest a relationship between emotional arousal and motor control under dual-task conditions. These findings are supported both by objective sensor data and subjective questionnaire responses. However, procedural improvements, such as standardized pacing through guided exercise videos and more controlled resting periods, are recommended to reduce variability and better isolate the effects of cognitive load.
For making predictive AI or machine learning algorithms for the Symphysis feedback loop the reliability of the current prototype is insufficient. Especially because the PPG sensor values were discarded and issues with the wrist module like skin contact emerged.
User feedback indicated that while the system was generally intuitive and comfortable, improvements to the wrist module's design and the visual feedback system are necessary. Specifically, clearer visual cues, avoidance of emotionally charged colours, and simpler explanations of technical terms will enhance user understanding and engagement.

This user-test study does not represent real knee rehabilitation scenario's, but before clinical trials can be done, a iteration on technical reliability and user interface needs to be done followed by another test with a large sample of healthy participants to see if the system is reliable enough for clinical use.
Future iterations should focus on addressing the technical limitations, refining the feedback presentation, and optimizing study protocols to enable more precise and generalizable conclusions. Overall, the Symphysis prototype shows strong potential as a tool for exploring the interplay between cognitive load, emotional responses, and motor control, but needs a more refined test were problems above are adressed to draw a definitive conclusion.

Discussion & Recommendations

This study aimed to design a patient centered wearable system for knee rehabilitation. Research showed that the rehabilitation journey requires a high degree of personalisation. Medical professionals work with established guidelines but continuously tailor treatment plans based on individual patient needs, goals, and medical history. These professionals play a crucial role not only in physical recovery but also in providing psychological guidance throughout the rehabilitation process.

During interviews, patients frequently mentioned psychological challenges associated with their injury. However, many struggled with aligning the physical and mental aspects of their rehabilitation. With a growing number of physiotherapists in the Netherlands leaving the field, patients are becoming increasingly responsible for their recovery at home, supported only by brief update sessions with professionals.

To address this issue, the solution concept developed in this study, Symphysis, aligns physical and psychological recovery through a unique event feedback loop.
Symphysis is a product-service system consisting of a wearable sensor kit with three sensor modules placed on the body. These modules detect both the biomechanics of the knee and physiological responses related to movement. Using Bluetooth, the data is transmitted to an app and a professional dashboard, where patients and physiotherapists can review and discuss events detected by the system. This facilitates conversations about psychological factors that may be influencing physical performance.

With this unique selling point, Symphysis occupies a strong position in the market. At a price of 499,99 euro, it is more affordable than many competitors. However, existing competitors often offer broader applications, while Symphysis currently focuses solely on knee rehabilitation. Therefore, further research is needed to explore the application of this approach to other rehabilitation processes, which could significantly broaden its market potential. In addition to broaden the scope of the concept different buisnessmodels should be explored like subrcription models and insurance involvement to make the sensorkit affordable for more patients

The design process primarily focused on the development of the wearable sensor kit to enable the Symphysis system. The interface and underlying processing algorithms still require development in future iterations. Nevertheless, this study lays the foundation for the UX/UI design, including onboarding experiences and the communication of rehabilitation metrics.

The final objective of this study was to validate the technical feasibility of the Symphysis concept. A functional prototype was developed and used in a user test. The prototype offers high refresh-rate motion analysis and tracks physiological metrics such as heart rate (HR), heart rate variability (HRV), and skin conductance (SC). Initial tests focused on accuracy, but long-term performance and consistency still require further validation. A future iteration using custom-designed electronics, as intended in the original concept, is recommended for more in-depth evaluation.

The user test consisted of three parts: a baseline measurement of physiological metrics, a test involving 15 bodyweight squats, and a test involving 15 bodyweight squats combined with a cognitive task (counting backwards in steps of seven). The user test revealed technical flaws in the prototype, especially in the wrist module, where the PPG sensor and skin contact posed a challenge for reliable readings. Furthermore, the test method, where the pace between tests was not controlled, allowed for different adaptation strategies by participants, which made comparison harder. Despite these challenges, the system detected significantly higher emotional arousal in the last test, together with greater compensation movements in internal and external rotation of the knee, showing that the Symphysis system has potential to detect the influence of cognitive load during movement. However, the flaws in the test method and prototype first need to be addressed in another design iteration, and the test repeated before drawing definitive conclusions.

The Symphysis prototype showed potential in detecting physiological responses related to movement. However, testing with healthy participants does not prove the system's effectiveness during real rehabilitation journeys. Therefore, after further development of the software, clinical trials will be essential to assess whether this system can significantly impact physiotherapy outcomes.

In addition, the hardware must be tested for compliance with CE regulations. To reduce costs and simplify production, future versions might integrate GSR sensors into existing smartwatches or wearables. This opens the possibility of using existing hardware in combination with commercial IMU tracking systems such as those offered by Movella.

The motivation behind this study stems from the startup initiative I co-founded, Exertise. Our original goal is to make home exercises more engaging by incorporating macro and micro gamification techniques, such as interactive exercises and motivational tracking systems similar to Duolingo's streak feature.
Although this project was conducted seperatly from Exertise, many aspects of Symphysis could benefit Exertise. A key takeaway is the value of integrating support for both physical and psychological aspects of rehabilitation. Implementing this in Exertise's interface could lead to a significant improvement in user experience. The measurement system showed potential, but the reliability of the system is debatable. After some more validation the Symphysis system could potentialy give Exertise a unique market position.

Conclusion

This study laid the groundwork for Symphysis, a patient-centered wearable system designed to align physical and psychological aspects of knee rehabilitation. Through interviews and user testing, the need for a personalized and psychologically supportive rehabilitation experience became evident, particularly as patients are increasingly responsible for their recovery outside clinical settings. Symphysis provides this need by combining biomechanical and physiological data in a platform that fosters meaningful conversations about psychological impact on movement recovery between patients and physiotherapists.

The development of the wearable sensor kit and a functional prototype demonstrated the potential technical feasibility of detecting emotional and physical responses during movement. Initial user tests highlighted the potential of the system to capture the effects of cognitive load on physical performance, although flaws in the prototype and testing method underscored the need for further iteration and validation. Future efforts must focus on refining the hardware, ensuring regulatory compliance, developing the app and dashboard interfaces, and conducting clinical trials to confirm the system's effectiveness in real knee rehabilitation programs.

Additionally, integrating Symphysis' insights into Exertise's broader platform could provide significant added value, enhancing user engagement through a more holistic approach to rehabilitation. Ultimately, with further development, Symphysis has the potential to fill a critical gap in the market, offering an affordable, targeted, and psychologically supportive rehabilitation tool that could significantly improve patient outcomes.

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Appendix

In this chapter additional background information about topics in the report is given. The relevant appendices to a speciific piece of text is refered to in the text above and can be identified by the letter.

Appendix A: Inform consent qualitative interviews

You are being invited to participate in a research study titled A patient-focused wearable for an engaging and supported knee injury recovery. This study is being done by Tim Bouwmeester from the Technical University of Delft. This is an internal TUD MSc thesis project from the faculty Industrial design engineering.

This research aims to better understand the rehabilitation process for knee injuries, including the needs and preferences of stakeholders (e.g., patients, healthcare providers) and exploring potential technological advancements. Your participation will help identify requirements for developing a patient-focused wearable device to improve knee rehabilitation outcomes.
You will be asked to participate in an interview lasting approximately 30–60 minutes. During the interview, you will be asked about your experiences, preferences, and suggestions for improving knee rehabilitation. The interview can be conducted in person or online via platforms such as Teams or Zoom, based on your convenience.
To ensure accuracy and avoid misinterpretation, audio recording will be preferred. The recording will be transcribed, and the audio file will be permanently deleted afterward. All data collected will be anonymized by participant number, meaning your identity will not be linked to your responses in any published or shared materials. If the participant prefers to not record audio, notes will be taken during the conversation.
All data will be stored securely in a password-protected database, accessible only to the student researcher and the supervision team. Any personal information collected for administrative purposes (signatures) will be deleted after the study is completed. Sensitive information in the final manuscript will be abstracted or removed to protect your identity.
While every effort will be made to safeguard your data, please note that online activities carry a small risk of data breaches. We will take the necessary precautions to minimize this risk.

Do you consent to the use of an audio recorder during our conversation? Please select your choice.

YES ☐ NO ☐

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions.

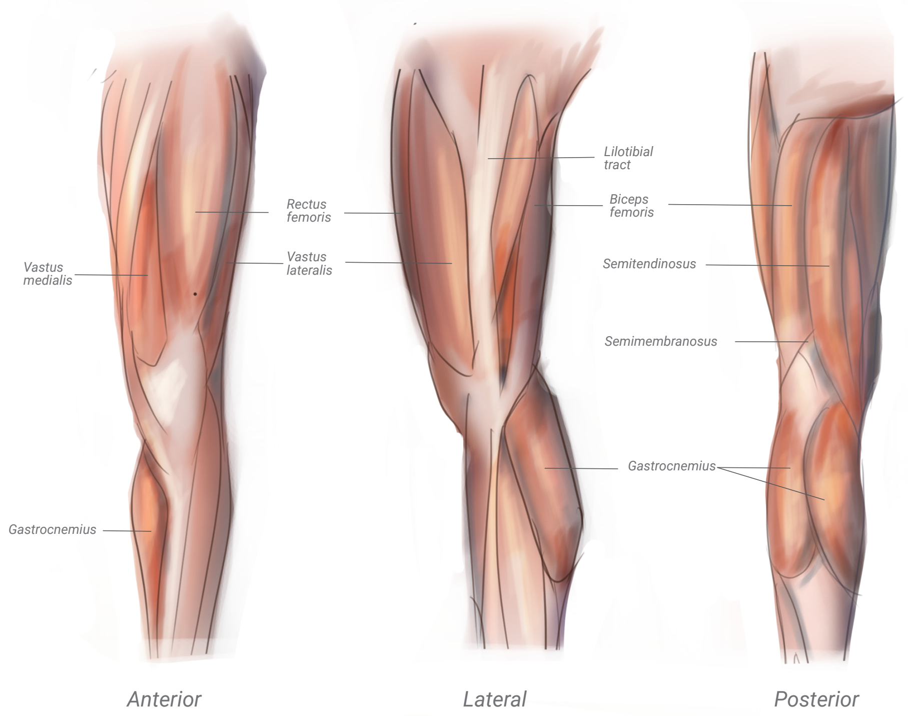
By signing this document, I confirm that I have read the informed consent document and agree to the use of my information for contribution to this research.

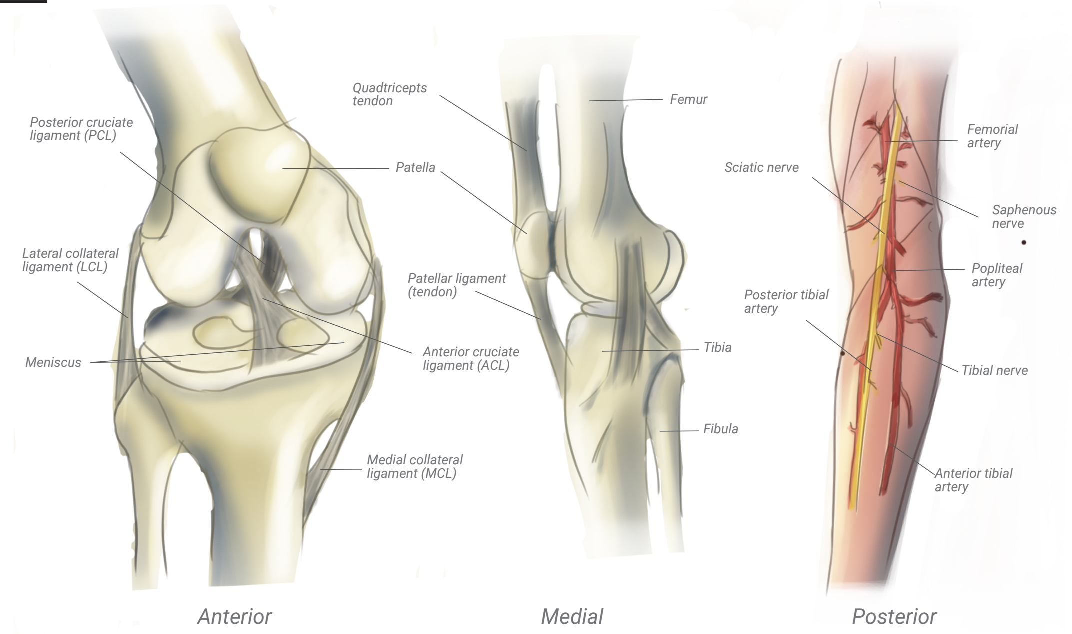
Appendix B: Detailed knee anatomy

Name	Type	Description	Function
Femur	Bone	Tigh bone, the bone that connect the hip-joint to the knee-joint	The femur is the upper component of the knee joint and forms the hinge with the tibia and patella. The lower end of the femur has two rounded condyles (the medial and lateral femoral condyles) that articulate with the tibial plateau
Tibia	Bone	The weight bearing bone that connects the knee joint to the ankle	The tibia forms the primary weight-bearing component of the knee joint. Its upper surface, known as the tibial plateau, has two shallow concave areas (medial and lateral) that receive the femoral condyles.
Patella	Bone	Kneecap; a small, flat, triangular bone in front of the knee.	The patella protects the knee joint and enhances the leverage of the quadriceps muscle, he patella also helps maintain proper alignment of the quadriceps tendon and reduces friction on the femur by gliding within the femoral groove as the knee flexes and extends
Fibula	Bone	Smaller bone on the outer side of the lower leg.	The upper part of the fibula forms a joint with the tibia, called the proximal tibiofibular joint, allowing slight movement between the bones that aids in flexibility. It also contributes to overall leg stability and aids in maintaining balance and proper alignment of the lower leg.
ACL (anterior cruciate ligament)	Ligament	The ACL originates from the medial (inner) side of the lateral femoral condyle and attaches to the anterior (front) aspect of the intercondylar eminence on the tibia, near the centre of the tibial plateau	ACL fibres prevent excessive forward movement (anterior translation) of the tibia relative to the femur. Additionally, the ACL controls rotational stability, especially during twisting or pivoting motions.
MCL (medial collateral ligament)	Ligament	The MCL originates from the medial epicondyle of the femur and it attaches to the medial (inner) aspect of the tibia, just below the knee joint, running along the inner side of the knee.	The MCL stabilizes the knee against valgus forces, which occur when there is an inward force on the knee, pushing it toward the opposite knee. This ligament is especially important in preventing excessive sideways movement and helping protect against injuries from impacts on the outer side of the knee. It works closely with the joint capsule and medial meniscus to support the knee.
PCL (posterior cruciate ligament)	Ligament	The PCL originates from the lateral (outer) aspect of the medial femoral condyle and it attaches to the posterior (back) part of the intercondylar area of the tibia, behind the ACL's attachment point	The PCL prevents the tibia from moving too far backward relative to the femur (posterior translation) and is especially active in stabilizing the knee when it's flexed (bent). Like the ACL, the PCL has two functional bundles that provide stability throughout knee motion. It's the strongest ligament in the knee and plays a critical role in high-impact or load-bearing movements.

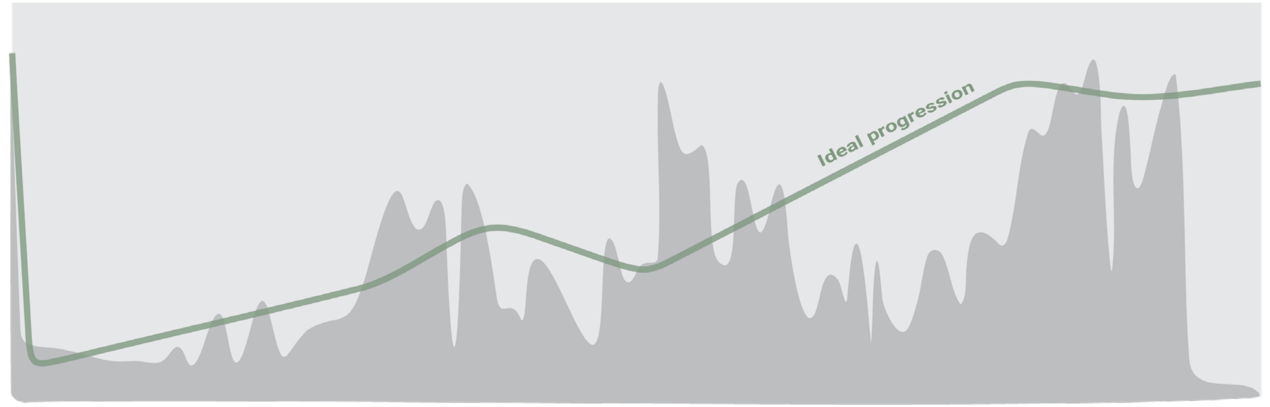
LCL (lateral colleterial ligament)	Ligament	The LCL originates from the lateral epicondyle of the femur and it attaches to the head of the fibula, the smaller bone located laterally beside the tibia in the lower leg	The LCL stabilizes the knee against varus forces, which push the knee outward, away from the opposite knee. This ligament plays a crucial role in preventing excessive outward movement of the knee, particularly in activities that involve side-to-side motion. It's more cord-like than the MCL and is not as directly connected to the knee joint capsule, giving it a unique structural function in knee stability.
Medial and Lateral Meniscus	cartilage	The medial and lateral menisci are two crescent-shaped, wedge-like pieces of fibrocartilage located on the tibial plateau (top of the tibia), between the femur and tibia	The menisci act as shock absorbers, evenly distributing the load across the knee joint during weight-bearing activities. They also play a crucial role in stabilizing the knee, improving congruency between the femur and tibia, and lubricating the joint by distributing synovial fluid. By reducing friction and cushioning the joint, the menisci protect the articular cartilage from excessive wear
Patellar ligament (patellar tendon)	ligament	The patellar ligament begins at the inferior (lower) border of the patella (kneecap). It attaches to the tibial tuberosity	the patellar ligament connects the quadriceps muscle group (front thigh muscles) to the tibia, allowing the knee to extend. When the quadriceps contract, they pull on the patella, which then pulls on the patellar ligament to straighten the knee. This ligament plays a major role in activities like kicking, jumping, and running. It also stabilizes the kneecap within the femoral groove, helping prevent dislocation.
Quadriceps Tendon	Tendon	Connects the quadriceps muscles to the patella.	Helps to straighten (extend) the knee joint.
quadriceps	Muscle group	The quadriceps muscle group is located on the front of the thigh. It consists of four muscles: the rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius.	The primary role of the quadriceps is knee extension, which involves straightening the knee. The quadriceps attach to the patella through the quadriceps tendon, and from there, the patellar ligament connects the patella to the tibia. When the quadriceps contract, they pull on the patella, which in turn pulls on the patellar ligament, causing the knee to straighten. The vastus lateralis and vastus medialis guide the patella's movement within the femoral groove. Imbalances in these muscles can cause improper tracking.
Hamstrings	Muscle group	The hamstrings are located on the back of the thigh and consist of three main muscles: the biceps femoris, semitendinosus, and semimembranosus.	The hamstrings are responsible for knee flexion, which involves bending the knee. When the hamstrings contract, they pull on the tibia, bringing it closer to the back of the thigh and bending the knee joint. The hamstrings help control knee extension and provide stability during activities that require rapid directional changes. Biceps femoris is also involved in externally rotating the femur.

Gastrocnemius	muscles	The gastrocnemius is the large, two-headed calf muscle located at the back of the lower leg. It runs from just above the knee to the Achilles tendon at the heel.	The gastrocnemius plays a minor role in knee flexion due to its origin just above the knee joint on the femur. When it contracts, it can help bend the knee slightly, particularly when the foot is planted on the ground. Although its primary role is ankle plantarflexion (pointing the toes downward), the gastrocnemius assists the hamstrings during knee flexion, especially when the foot is not weight-bearing.





Appendix C: Detailed patient journey



	Injury	Seeking help	Diagnosis	Prehabilitation	Medical procedure	Normalize movement	Strenghtening	Functional training	Return to normal activity	Re-injury
Activities	Knee injuries arise from sudden events like ligament tears or gradual issues like aging or poor footwear. Many self-manage with cooling or massage, but proper care ensures effective recovery.	Help for knee injuries includes visiting a GP, seeking emergency room care for severe cases, or consulting a primary care physiotherapist to begin appropriate rehabilitation and recovery strategies.	Diagnosis involves discussing the injury and medical history, conducting physical exams with maneuvers and visual inspections, and, if needed, using secondary care tools like MRI or X-rays for further assessment.	Prehabilitation focuses on lifestyle adjustments, attending physiotherapy, restoring range of motion, reducing inflammation, swelling, and effusion, and effectively managing pain to prepare for optimal surgery recovery.	Medical procedures may involve surgery, injections, or medications to address the injury and support recovery effectively. Often the patient receives a rehabilitation protocol from the hospital. For example using a cast or restricting brace for healing	The first phase of rehabilitation focuses on modifying daily activities, promoting healing, restoring range of motion, controlling inflammation and effusion, gait training, and modulating pain to normalize movement effectively.	The strengthening phase emphasizes regaining full range of motion, normalizing gait, progressing from basic to advanced strength and flexibility exercises, improving cardiovascular conditioning, and incorporating proprioception training.	The functional training phase focuses on sport- or occupation-specific drills, preparing for a return to normal activities, and enhancing proprioception and coordination for optimal performance.	Returning to normal activity involves resuming sports, maintaining mobility through exercises, staying active, and focusing on injury prevention.	Re-injury may involve damage to the original injury site or affect supporting structures or the opposite leg.
Emotions & pain points	Knee injury can bring frustration, pain, and worry, leading individuals to self-manage while hiding their struggles to avoid burdening others. Adjusting movements to avoid pain, isolation, and reduced quality of life often accompany the emotional toll of recovery.	Seeking help can evoke feelings of being a burden, doubt about needing or deserving professional care, fear of medical interventions, and concerns over the time and financial resources required for treatment.	Diagnosis can bring uncertainty and health worries, decision-making fatigue, and feeling overwhelmed. Social and professional expectations, established illness beliefs, and the exhaustion of repeatedly explaining the injury add to the emotional strain.	Prehabilitation involves building trust with medical professionals, accepting a temporarily reduced quality of life, adapting to lifestyle changes, coping with isolation, and managing fear of medical interventions, all of which can be emotionally challenging.	Medical intervention can bring stress, fear of the outcome, anxiety about pain, but also relief and excitement that steps are being taken to address the injury.	The first stage of rehabilitation involves patience, adapting movements, and managing boredom from basic exercises. It can bring reliance on others, loneliness, self-image concerns, and a need for social interaction, balanced by a positive start and managing load versus capacity.	The strengthening phase can feel slow and effort-intensive, leading to loss of confidence. Balancing load versus capacity remains challenging but essential for building strength and maintaining steady progress.	The functional training phase brings anxiety about reinjury and the challenge of confronting past abilities through muscle memory. However, it fosters hope for returning to activity while continuing to manage load versus capacity effectively.	Returning to normal activity brings mixed feelings of confidence, lingering caution, and enthusiasm balanced with anxiety about future health. Without professional guidance, guilt over missed maintenance exercises and managing load versus capacity add to the emotional complexity.	Re-injury often brings guilt, hopelessness, and frustration, alongside deep concerns about the future and the potential long-term impact on health and mobility.
Stakeholders	The patient navigates the injury with support from their social circle. Businesses may address workplace adaptations, while insurance companies assess coverage for care, initiating a network of healthcare providers like GPs and physiotherapists.	The patient engages with GPs and physiotherapists to identify injury severity. Insurance companies evaluate eligibility for consultations, and the social circle provides emotional encouragement and logistical assistance.	The GP and orthopedic surgeon collaborate on advanced imaging and assessments. Insurance companies approve necessary procedures, while the patient, guided by their social circle, makes decisions about care amidst work and lifestyle concerns.	Physiotherapists guide patients through exercises and lifestyle changes. Family and friends support emotional well-being, and employers accommodate reduced mobility. Insurance companies ensure financial support for therapy, with the government promoting	Orthopedic surgeons lead interventions, assisted by physiotherapists during post-procedure recovery planning. Insurance companies manage surgical costs, while family members provide immediate care and emotional support during	Physiotherapists work closely with patients to restore function, while the social circle aids with daily activities. Employers and businesses adapt to temporary mobility limitations, and insurance covers rehabilitation costs.	Patients engage with physiotherapists to regain strength and mobility. Social circles and businesses support gradual work re-entry, while insurers cover therapy. Government policies ensure accessibility to strengthening programs.	Physiotherapists prepare patients for real-world activity, balancing health goals with safety. The social circle encourages progress, while insurers and employers support recovery with financial aid and workplace flexibility.	The patient balances work and personal life with ongoing maintenance exercises. Businesses and employers support reintegration, family and friends offer encouragement, and insurance ensures continuity of care for injury	The patient seeks renewed care from GPs, physiotherapists, and surgeons, with insurers reassessing coverage. The social circle provides emotional and logistical support, while employers adapt to renewed limitations.
Opportunities	• Early detection of improper movement patterns can help prevent further damage, allowing for immediate, informed decisions. • Real-time stress and pain monitoring empowers the patient to manage emotional and physical responses, reducing anxiety and preventing overexertion. • Accurate tracking of pain levels offers reassurance, ensuring that the user takes timely action, leading to better outcomes and less	• The wearable's data can objectively demonstrate the severity of the injury, reducing self-doubt and encouraging prompt action to seek care. • The combination of physical and emotional indicators reassures the patient by showing them that help is necessary, guiding them to the right healthcare provider. • Clear, actionable insights into the injury's progress or risk promote a proactive approach, minimizing delays in treatment	• Real-time data sharing allows healthcare providers to make faster, more informed decisions, reducing the patient's worry and uncertainty during the diagnostic process. • Tracking both physical and psychological factors can ensure a holistic diagnosis, addressing not only the injury but also the emotional impact of the situation. • Empowering patients with data on their condition boosts confidence in their recovery, helping them feel in control of their journey.	• Personalized feedback during prehabilitation exercises boosts motivation and engagement, as patients can track their progress and see tangible improvements in both movement and strength. • By monitoring stress and fatigue, the wearable ensures patients don't overexert themselves, preventing early setbacks and building trust in the process. • The integration of both physical and emotional data helps patients stay committed to their rehabilitation goals by fostering a sense of control and achievement.	• During medical interventions like injections or other medicactions. Monitoring pain or stress can help proffesionals acounting for the patient emotional stress during these interventions • During surgery there is not much a wearable can do. During surgery where the patient is awake, stress and pain detection could be helpfull, if it is not interfering with the procedure. • Monitoring direct after surgery for infection, inflamation and pain could be benefitial.	• Tracking and improving movement patterns ensures the patient gradually regains function, boosting confidence in their body's ability to heal. • Monitoring stress and pain helps avoid setbacks, ensuring patients don't push beyond their capacity, thus fostering a positive relationship with their rehabilitation journey. • Encouragement through positive feedback about restored movement or pain reduction strengthens resilience, reinforcing the progress being made.	• Personalized progress tracking ensures the patient sees their efforts paying off, building both physical strength and mental resilience. • Balancing effort and recovery by monitoring stress helps patients stay within safe boundaries, preventing discouragement from overexertion or underperformance. • By tracking improvements in muscle engagement, the wearable helps shift the focus from setbacks to growth, reinforcing a sense of accomplishment.	• Real-time feedback ensures functional exercises are performed correctly, reducing the fear of reinjury and building trust in the body's readiness to return to normal activities. • The combination of movement and emotional data helps patients manage anxiety, providing them with tailored support as they progress toward regaining full function. • Seeing measurable progress toward personal goals encourages continued effort, helping patients stay motivated throughout challenging	• Ongoing monitoring of reinjury risk ensures the patient feels confident in returning to regular activity, knowing they're not pushing beyond their body's capacity. • Balanced emotional and physical tracking helps the patient manage anxiety about reinjury while providing reassurance of their capability to function at a normal level. • Positive reinforcement through visible recovery milestones fosters a sense of accomplishment, motivating the patient to maintain recovery habits long-term.	• Early detection of reinjury risk gives the patient the chance to adjust their behavior before a major setback, reducing feelings of guilt or hopelessness. • Monitoring emotional resilience empowers patients to seek timely support, preventing isolation and ensuring that both mental and physical health are prioritized. • Providing actionable insights on both physical and emotional recovery reduces uncertainty, allowing patients to bounce back more quickly and with confidence.

2 Weeks - ~2 years

Appendix D: Acute knee injury mechanisms

Type of injury	Mechanism of injury	Historical findings	Is the injury common?
ACL	Non-contact: twisting pivoting with planted foot, hyperextension, sudden deceleration, forced internal rotation	Immediately disabled and unable to continue activity with extreme pain at time of injury. Often feels/hears a "pop". Swelling within 1-2 hours. Knee joint is very tense and painful.	Second common ligament injury
MCL	Valgus (lateral) contact or external rotation force with the foot firmly planted, (ACL often damaged also, if exogenous force (force form outside the body) is sufficient	Localized swelling, Effusion (buildup of fluid) in less than 12 hours	Most common ligament injury
Meniscus	Medial meniscus 3 times more likely to tear than lateral meniscus. Usually, a non-contact rotational force applied to a partly or completely flexed knee (often coexist with ACL tear)	Effusion develops more than 12 hours after injury, painful locking, clicking or "giving away" of the knee. Stiffness in knee is also very common	common
LCL	Caused by varus (medial stress or rotational force when the foot is planted or hyperextended.	Localized pain and mild effusion that develops in within a few hours of injury	rare
PCL	Often caused by anterior blow to the Tibia with the knee flexed.	Localized pain and mild effusion that develops in within a few hours of injury	rare
Patella dislocation and fractures	Always occurs on the lateral side and happens more often with the patient. Happens when the foot is planted and the femur rotates medially. This can also happen by an exogenous force to the lateral side of the knee or the medial edge of the patella. A fracture occurs from an anterior blow to the knee	Patella is out of the femoral groove, pain	

Appendix E: Overuse knee injury mechanisms

Type of injury	Mechanism of injury	History findings	Is the Injury Common?
Patellofemoral Syndrome (PFS)	Improper tracking of the patella in the femoral groove; repetitive weight-bearing activities; malalignment issues (e.g., wide Q angle, genu valgum).	Chronic anterior knee pain (retro patellar or peripatellar); worsens with activity, stairs, or prolonged sitting; usually no acute trauma reported.	Common, especially in athletic young women.
Knee Tendonitis	Overuse from increased activity intensity or duration; often affects runners and joggers.	Pain around the tendon areas, often in the patellar or quadriceps tendons; symptoms develop gradually with increased activity.	Common in runners and athletes who increase training intensity suddenly.
Iliotibial Band Friction Syndrome (IBFS)	Repetitive flexion/extension causes friction of iliotibial band over lateral epicondyle; worsened by genu varum (bow legs).	Diffuse lateral knee pain, worsens with long or hilly runs; pain climbing stairs or with prolonged activity.	Common among novice runners and those who train on hilly terrain.
Prepatellar Bursitis	Chronic irritation from prolonged kneeling (e.g., in occupations like carpet laying); also, from acute trauma.	Localized swelling and tenderness over the front of the knee; may feel warm if infected; typically reports prolonged kneeling or direct trauma history.	Common in occupations requiring prolonged kneeling (e.g., carpet layers, wrestlers).
Osteoarthritis	Age-related degeneration and previous injuries increase risk	Start-up difficulty and stiffness improves after more movement, grinding sensation, pain flair-ups, giving aways of the knee, reduced range of motion	Common especially in older people
Pes Anserine Bursitis	Overuse from repetitive activity, often affecting runners; inflammation at the medial knee bursa.	Medial knee pain and localized tenderness at the pes anserine area; may worsen with climbing stairs or prolonged physical activity.	Common in runners and athletes with repetitive knee strain.

Appendix F: Physical examination maneuvers

Manoeuvre name	Purpose	How to perform	Confirming injury sign
Bulge Sign	Assess for effusion	Apply lateral pressure on patella in supine position.	Medial fluid wave
Valgus Stress Test	Evaluate MCL stability	Apply medial force to knee with ankle stabilized laterally (10–15° flexion and full extension).	Increased movement (laxity)
Varus Stress Test	Evaluate LCL stability	Apply lateral force to knee with ankle stabilized medially.	increased movement (laxity)
Lachman Test	Assess ACL integrity	Flex knee 20–30°; stabilize femur and pull tibia anteriorly.	Excessive motion, soft endpoint
Anterior Drawer Test	Assess ACL integrity	Flex knee 90°; pull tibia anteriorly.	Excessive forward movement
Posterior Drawer Test	Assess PCL integrity	Flex knee 90°; push tibia posteriorly.	Excessive backward movement
Posterior Sag Test	Assess PCL integrity	Flex hip/knee 90°; observe for posterior tibial sagging.	Visible sagging
McMurray Test (Medial)	Assess medial meniscus	Flex knee 90°, apply varus stress with external rotation; extend knee.	Pain or clicking
McMurray Test (Lateral)	Assess lateral meniscus	Apply valgus stress with internal rotation.	Pain or clicking
Patellar Apprehension Test	Assess patellar instability	Move patella laterally at 30° flexion.	Apprehension or quadriceps contraction
Clarke's Sign	Assess patellofemoral dysfunction	Press above patella during quadriceps contraction.	Pain or inability to sustain contraction

Appendix G: Medical interventions

Surgical procedures

Procedure	*Description & Purpose*	*Common Uses*	*Considerations/Outcomes*
Arthroscopy	*Minimally invasive surgery using a small camera to examine and treat knee issues.*	*Meniscal repairs, cartilage repair, mild ligament damage*	*Less invasive with faster recovery time.*
Meniscectomy or Meniscal Repair	*Removal (meniscectomy) or repair of torn meniscus using sutures.*	*Meniscal tears causing knee instability or locking*	*Repair preferred for younger, active patients to reduce arthritis risk.*
Ligament Reconstruction (e.g., ACL)	*Replacing a torn ligament with a graft from patient's tendons (autograft) or a donor (allograft).*	*Torn ACL/PCL in young or active individuals needing stability*	*Extensive post-op rehab required for functional restoration.*
Osteotomy	*Realignment surgery involving bone cutting and reshaping to relieve pressure on damaged area.*	*Early-stage arthritis in younger patients*	*Helps delay total knee replacement; reduces pain and improves function.*
Cartilage Restoration	*Techniques like microfracture, osteochondral grafts, or autologous chondrocyte implantation to regenerate cartilage.*	*Focal cartilage defects, especially in younger patients*	*Often successful in reducing pain, preserving joint function.*
Total or Partial Knee Replacement (Arthroplasty)	*Damaged cartilage and bone are replaced with metal/plastic components, recreating the knee joint.*	*Severe osteoarthritis or irreversible joint damage*	*Implants last 15-20 years; younger patients may need revisions.*

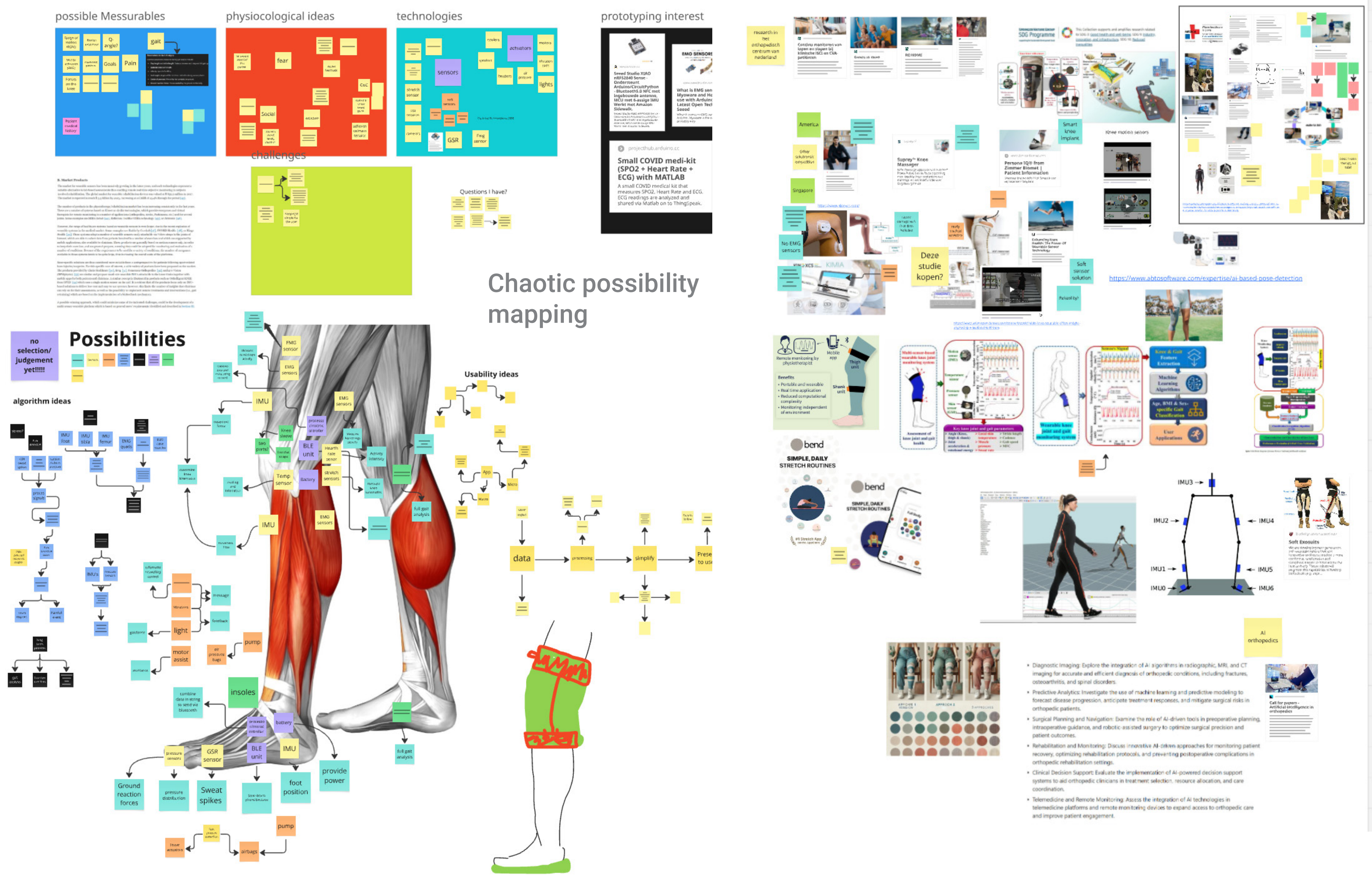
Medications

Medication	*Description & Purpose*	*Common Uses*	*Considerations/Outcomes*
NSAIDs (e.g., Ibuprofen, Naproxen)	*Reduces pain and inflammation; prescribed short-term post-injury or surgery.*	*Post-injury or post-surgical pain management*	*Long-term use can cause stomach and cardiovascular issues.*
Corticosteroid Injections	*Reduces inflammation, providing short-term pain relief.*	*Arthritis or persistent knee joint inflammation*	*Not recommended for frequent use as it can weaken tendons/cartilage.*
Hyaluronic Acid Injections	*Provides joint lubrication, shock absorption, and pain relief.*	*Osteoarthritis for patients unresponsive to other treatments*	*Effects are temporary, typically lasting weeks to months.*
Platelet-Rich Plasma (PRP) & Stem Cell Therapy	*PRP promotes tissue repair using platelets; stem cells support tissue regeneration.*	*Cartilage injuries, early arthritis, and tendon damage*	*Limited long-term evidence, but some report functional improvements and pain relief.*
Antibiotics	*Used for bacterial infections, especially post-surgery to prevent infection.*	*infected bursitis or surgical infection prevention*	*Often administered intravenously for severe infections; oral antibiotics for milder cases.*

Appendix H: different type of braces

Type of knee brace	Application	Effect on biomechanics
Prophylactic Knee Braces	Designed to prevent injuries, commonly used in contact sports	Reduces lateral and medial knee joint forces, helps in stabilizing the knee, and limits excessive range of motion to prevent ligament injuries (especially MCL).
Functional Knee Braces	ACL, PCL, MCL, or LCL injuries, especially post-surgical or post-injury	Provides support and restricts abnormal motion, helping to restore normal movement patterns while offloading stress from the injured ligament or joint.
Rehabilitative Knee Braces	Post-operative recovery, acute injury stabilization	Limits knee joint movement to facilitate healing, typically restricting knee flexion and extension to prevent re-injury and allowing controlled range of motion.
Unloader / Offloader Braces	Knee osteoarthritis, usually for pain on one side of the knee	Redistributes load across the knee joint, decreasing stress on the affected compartment, which can help relieve pain and improve gait in osteoarthritis patients.
Patellofemoral Knee Braces	Patellofemoral pain syndrome, patellar dislocations or instability	Improves tracking of the patella, stabilizes it to reduce pain and prevent dislocations, and may reduce anterior knee pain by aligning the patella properly.
Compression Sleeves (Knee Sleeves)	Mild knee pain, minor inflammation, mild joint instability, arthritis	Provides light compression and warmth, which can improve proprioception, reduce swelling, and offer minimal stability without significantly altering joint biomechanics.
Hinged Knee Braces	Ligament injuries, meniscal tears, moderate to severe knee instability	Provides medial-lateral support to the knee, restricts certain knee movements to prevent further damage, and stabilizes the knee joint during dynamic activities.

Appendix I: Ideation brainstorm



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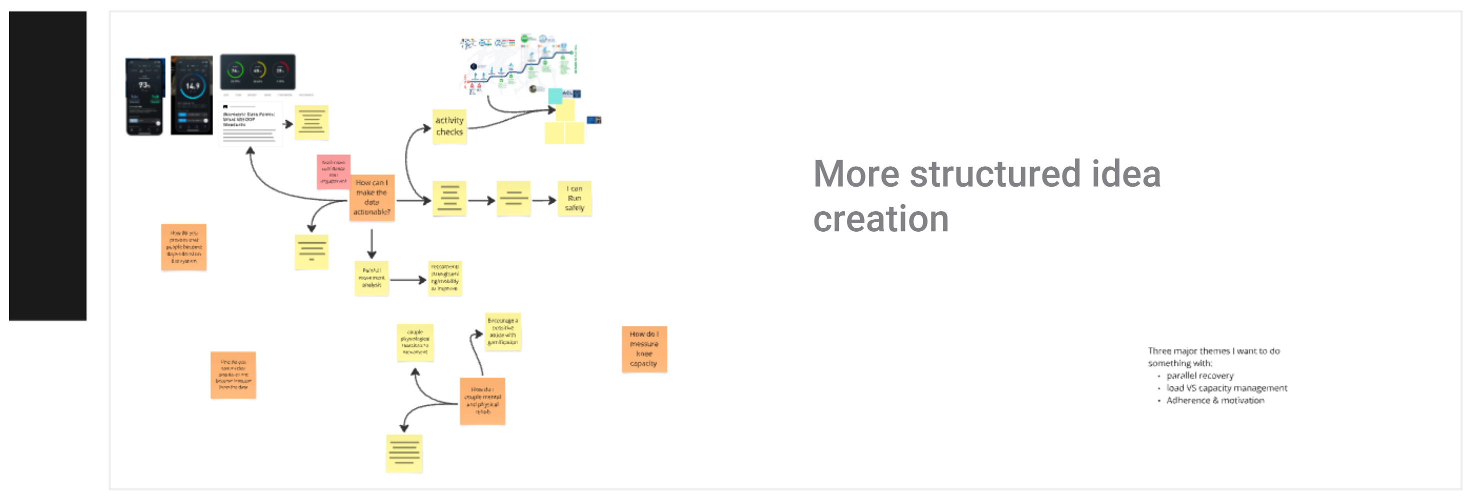
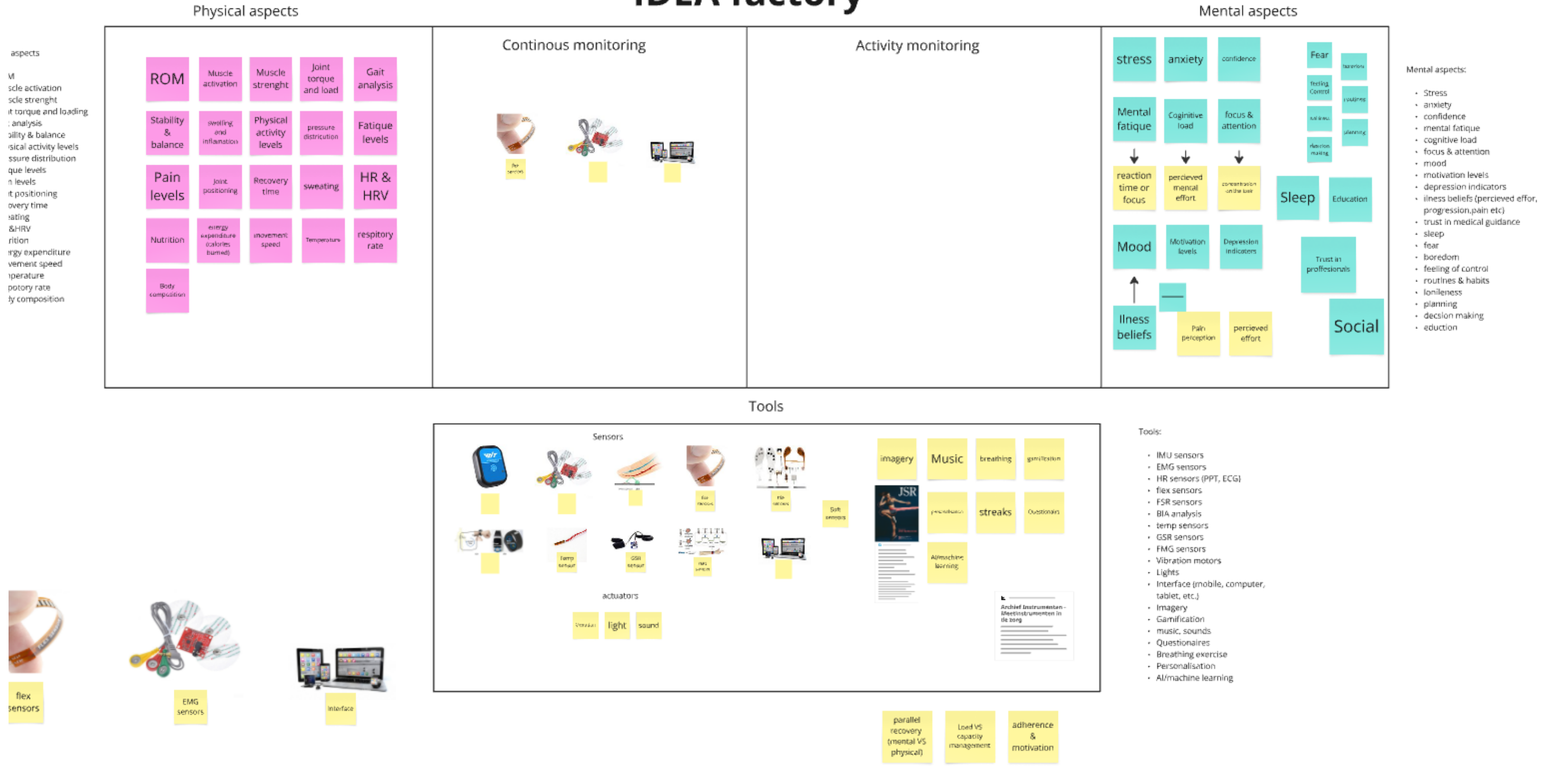
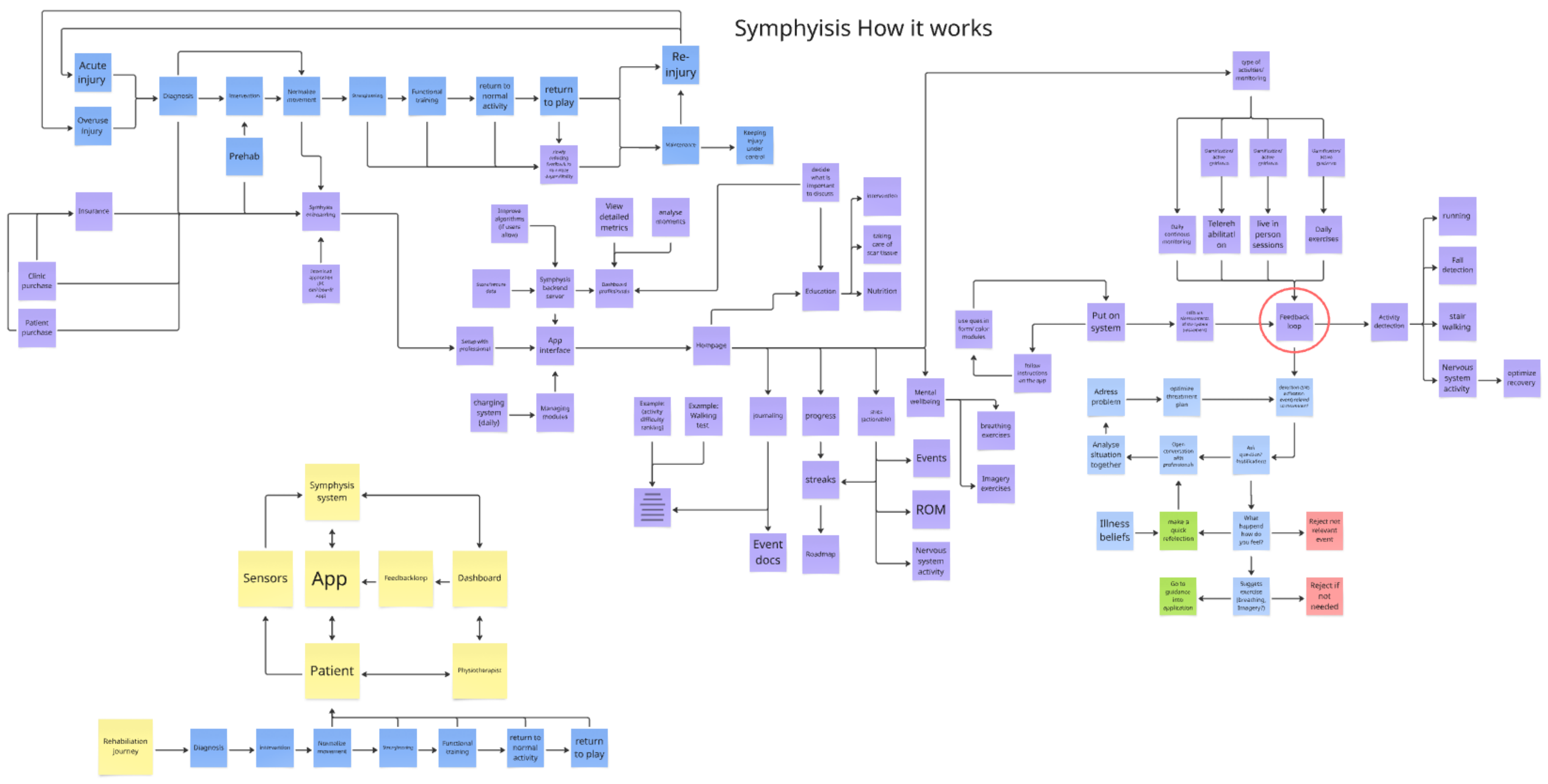


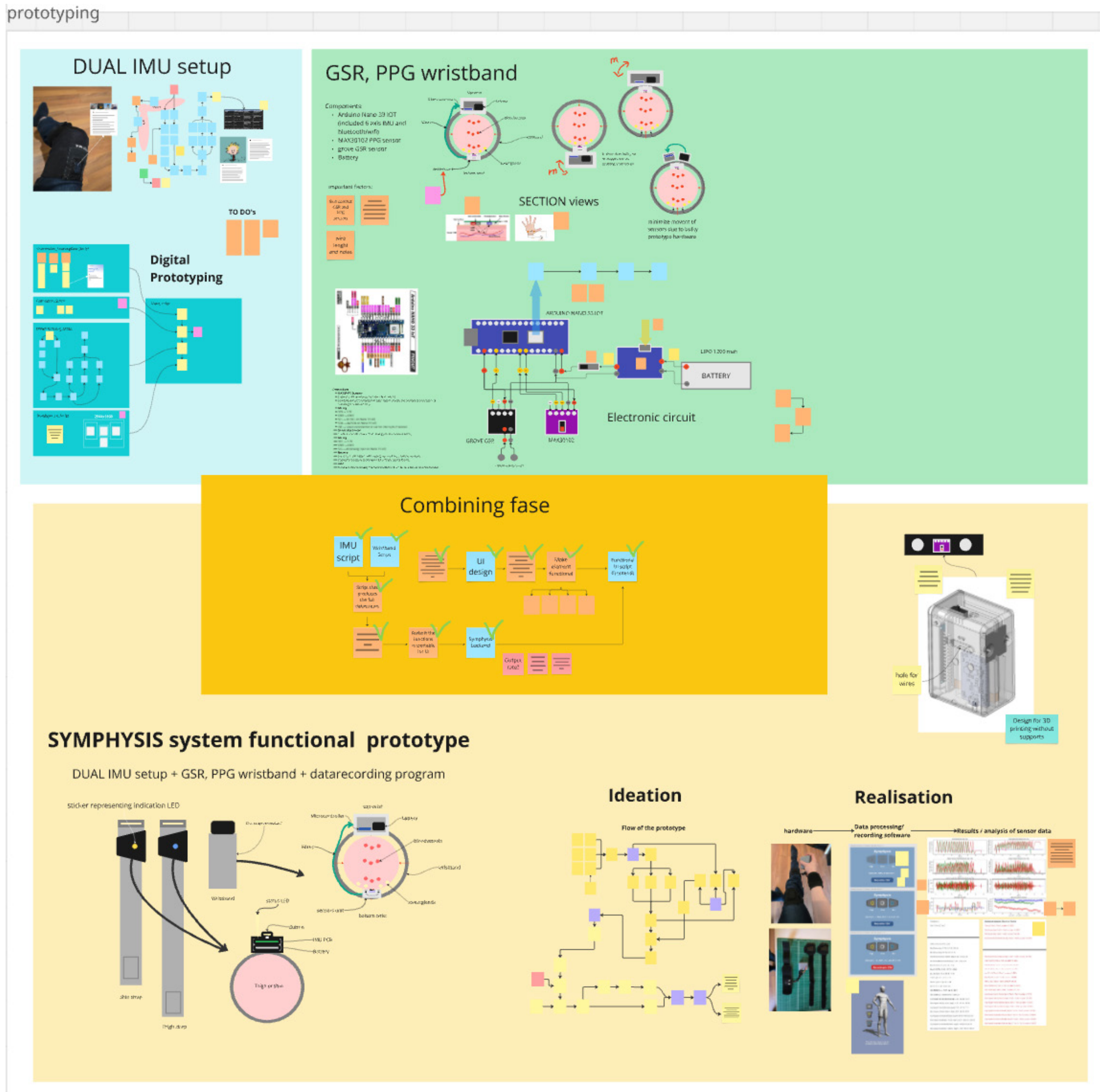
IDEA factory



Appendix J: Symphysis system development

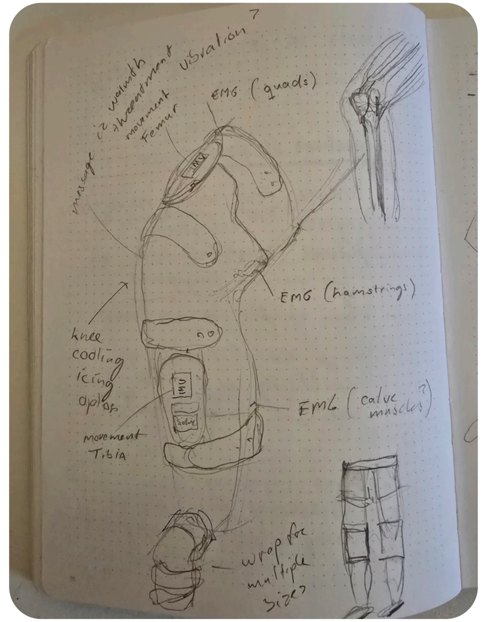


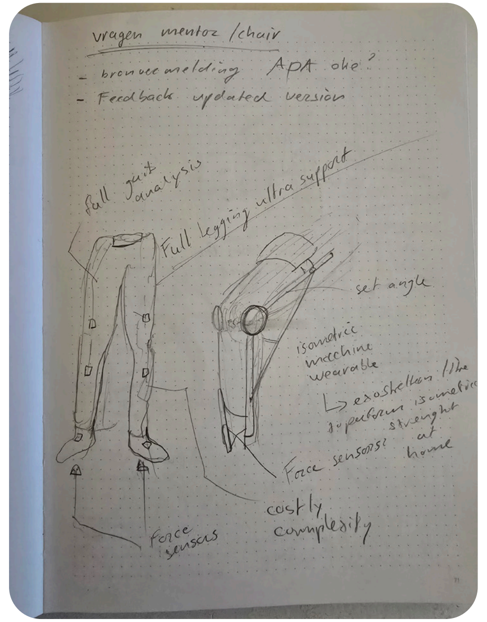
Appendix K: Prototyping proces

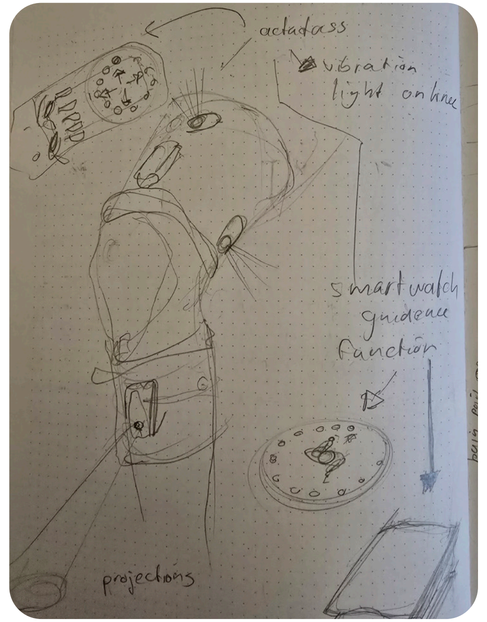


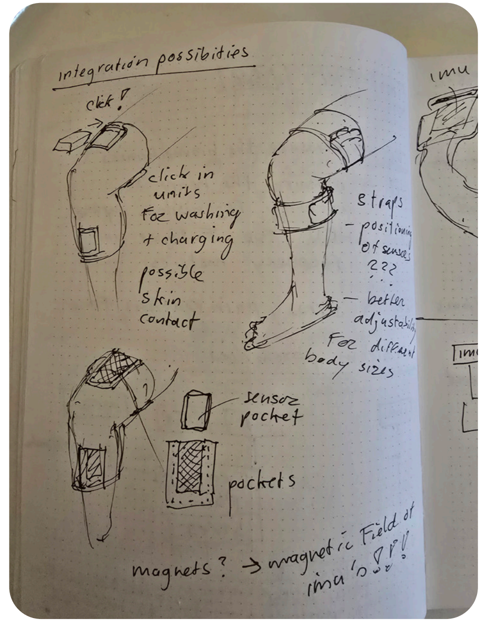
The prototyping proces shows the structured aproach of making and testing individual parts of the prototype and combining them into the functional prototype.

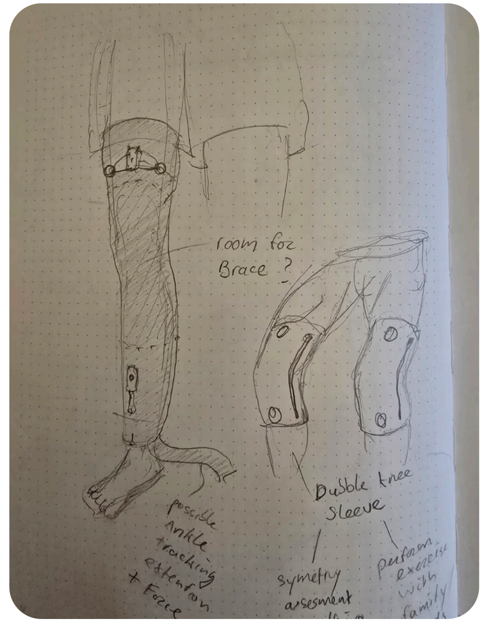
Appendix L: IDEA sketches

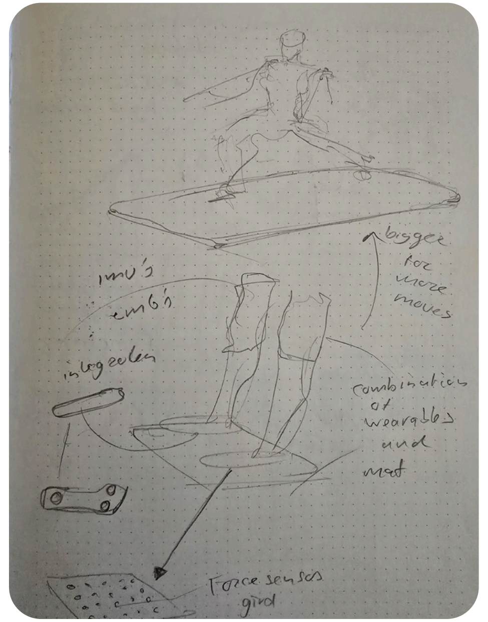


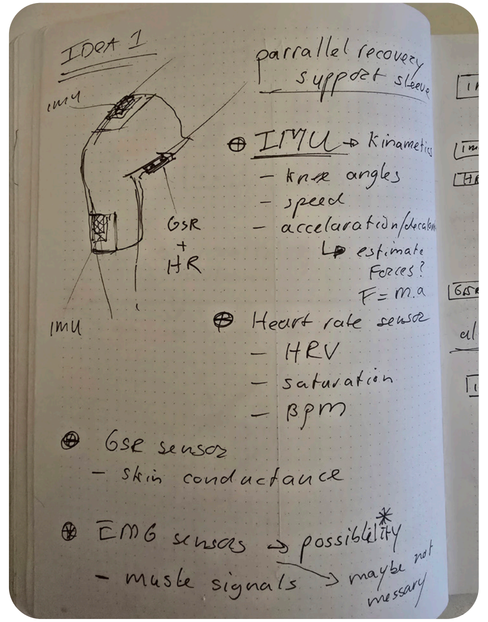


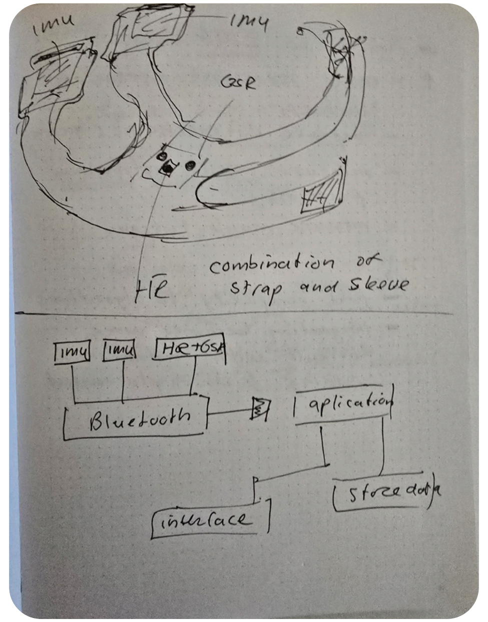


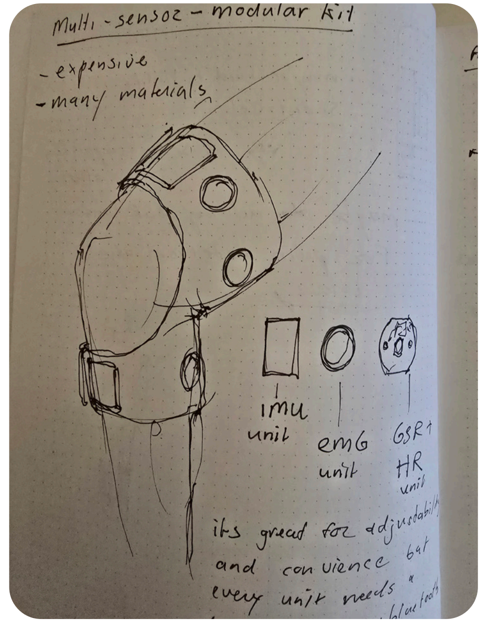


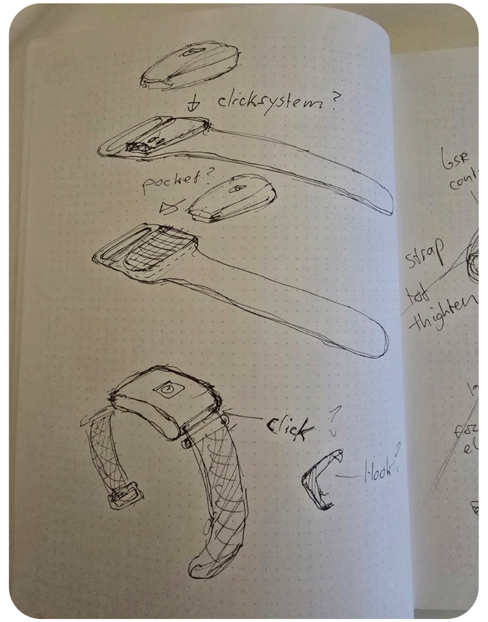












Appendix M: Brochure testing

Symphysis: Brengt lichaam en geest samen in knie revalidatie

Wat doet Symphysis?
Symphysis is een slimme, innovatieve oplossing die helpt om mentale en fysieke herstelprocessen op elkaar af te stemmen. Door emoties en bewegingen met elkaar te verbinden, krijgen zowel de patiënt als de fysiotherapeut waardevolle inzichten. Dit maakt het herstel niet alleen effectiever, maar ook persoonlijker.

Hoe werkt Symphysis?
Symphysis is een draagbaar systeem dat continu informatie verzamelt via sensoren die je gedurende de dag draagt. Dit systeem combineert gegevens over hoe je je voelt met hoe je beweegt. Door sensoren die je lichamelijke reacties op emoties meten te koppelen aan bewegingssensoren, kan Symphysis momenten herkennen waarop emoties zoals stress, pijn of ongemak samenhangen met je kniebewegingen. Via een eenvoudige, interactieve app kun je deze inzichten bekijken en reflecteren op je vooruitgang. Voor de fysiotherapeut is er een overzichtelijk dashboard met alle belangrijke gegevens om het behandelplan te verbeteren gebaseerd op gemeten data en jouw perspectief daarop.

De voordelen voor de patiënt:
- Begrijp beter hoe emoties en bewegingen samenhangen.
- Ontvang op maat gemaakte oefeningen voor zowel lichamelijke als mentale uitdagingen.
- Voel je meer betrokken bij je herstelproces dankzij duidelijke, visuele inzichten.

De voordelen voor de fysiotherapeut:
- Inzicht in mentale en fysieke barrières die het herstel beïnvloeden.
- Gebruik data om het gesprek aan te gaan en gerichte begeleiding te bieden.
- Creëer een behandelplan dat is afgestemd op zowel mentale als lichamelijke klachten voor een parallel herstel
- Inzicht in bewegingen (bewegingsbereik en snelheid)

Waarom Symphysis?
Symphysis helpt niet alleen om de knie te herstellen, maar ook om vertrouwen en motivatie op te bouwen. Het is een moderne, persoonlijke aanpak die lichamelijke en mentale aspecten in balans brengt voor een compleet herstel.

ParityMotion: Gebalanceerde knie revalidatie

Wat doet ParityMotion?
ParityMotion is een geavanceerd draagbaar hulpmiddel dat helpt om de balans tussen je benen te herstellen en de belasting op je knie te optimaliseren. Het combineert gedetailleerde gegevens over hoe je beweegt met jouw eigen beleving van je blessure. Dit geeft zowel jou als je fysiotherapeut de inzichten die nodig zijn voor een veilig en effectief herstel.

Hoe werkt ParityMotion?
ParityMotion analyseert nauwkeurig hoe je je benen gebruikt tijdens bewegingen doormiddel van twee kneesleeves op de knieen van de patient. Het vergelijkt de spieren en beweging van je geblesseerde been met je gezonde been en herkent onevenwichtigheden. Via een handige app wordt dit inzichtelijk en kun je reflecteren op jouw voortgang.

De voordelen voor de patiënt:
- Begrijp hoe je knie herstelt door duidelijke en visuele vergelijkingen met je gezonde been.
- Werk aan een veilig herstel met gepersonaliseerde feedback en oefeningen.

De voordelen voor de fysiotherapeut:
- Zie waar onevenwichtigheden en asymmetrieën zitten.
- Gebruik objectieve data om jouw expertise te ondersteunen en betere begeleiding te bieden.
- Monitor spieractivatie, Bewegingsbereik, looppatronen en het perspectief van de patient hierop voor een compleet herstelbeeld.

Waarom ParityMotion?
ParityMotion maakt revalidatie slimmer en efficiënter. Door een unieke combinatie van beweging en beleving geeft het jou en je fysiotherapeut de tools om blessures grondig aan te pakken. ParityMotion brengt je een stap dichter bij een sterker en gebalanceerd herstel.

MoveSphere: Eenvoudig, toegankelijk en motiverend knie herstel

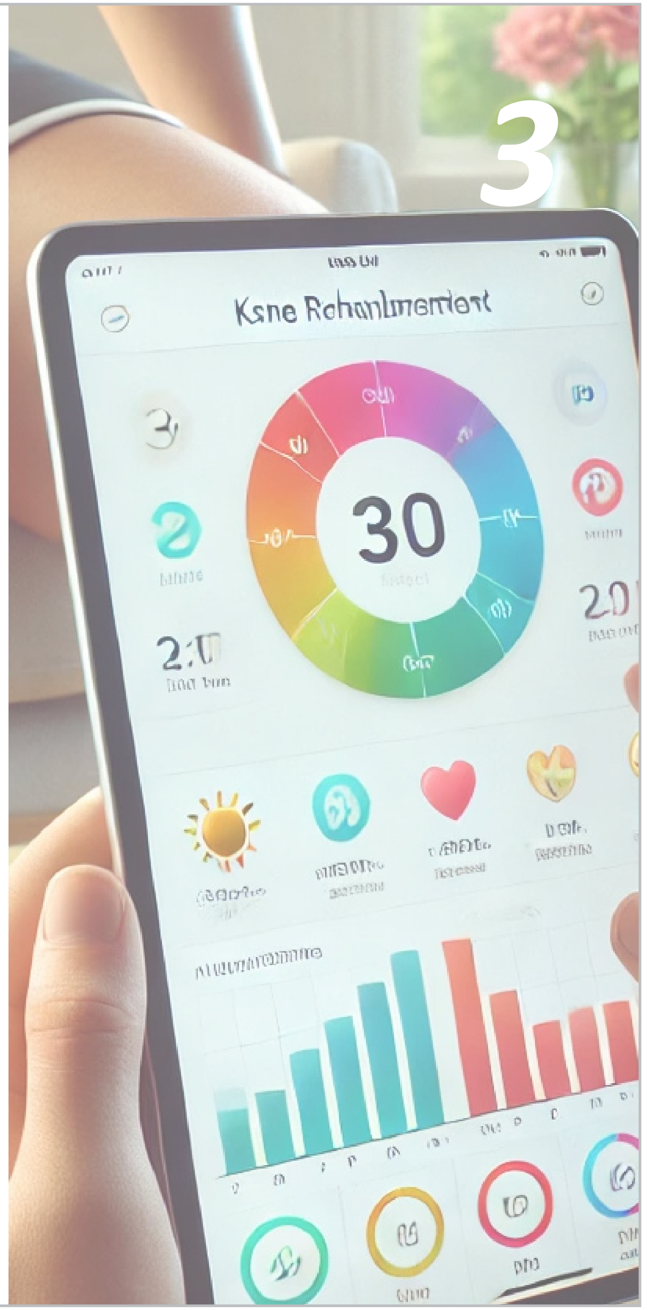
Wat doet MoveSphere?
MoveSphere is een slimme en intuïtieve oplossing die revalidatie leuk en toegankelijk maakt. Door het combineren van eenvoudige technologie met een gebruiksvriendelijke digitale interface, helpt MoveSphere je om gemotiveerd te blijven en je herstel stap voor stap te volgen. Het biedt een moderne aanpak die zowel je fysieke als mentale herstel ondersteunt.

Hoe werkt MoveSphere?
MoveSphere gebruikt compacte sensoren om je bewegingen tijdens de revalidatie te meten. De bijbehorende app zet traditionele vragenlijsten om in een interactieve en speelse ervaring, waardoor je actief
betrokken blijft bij je herstel. Door jouw voortgang te koppelen aan eenvoudige, leuke uitdagingen, blijf je gemotiveerd om je
oefeningen vol te houden.

De voordelen voor de patiënt:
- Je blijft gemotiveerd met een gamified proces.
- Je Krijgt inzicht in je herstel door duidelijke feedback over je bewegingen en voortgang.
- Je ontdek de link tussen overtuigingen en fysieke prestaties via een toegankelijke interface.

De voordelen voor de fysiotherapeut:
- Toegang tot een overzichtelijke weergave van de voortgang van de patiënt.
- Begrijp hoe mentale factoren zoals overtuigingen herstel beïnvloeden.
- Werk met een systeem dat consistent gebruik stimuleert en waardevolle gegevens verzamelt.

Waarom MoveSphere?
MoveSphere maakt revalidatie simpel, leuk en effectief. Het biedt een moderne manier om je herstel te volgen zonder ingewikkelde of dure technologie. Met zijn focus op gebruiksgemak, betrokkenheid en
toegankelijkheid is MoveSphere dé oplossing voor iedereen die een stap vooruit wil zetten in knie rehabilitatie.



Appendix N: POR

Program of requirements

The program of requirements is build using the MoSCoW method making a clear seperation between priorities of different requirements.

Must have

1. Physical Reactions to Emotions: The device could measure physical responses (e.g., heart rate, galvanic skin response) related to emotional states.
2. Knee Flexion and Extension Tracking: The wearable must accurately measure knee flexion and extension angles with a precision of 1°.
3. Angular Velocity Tracking: The wearable must track angular velocity, acceleration and Jerk.
4. The system must be able to detect changes in GSR, HR and HRV.
5. Comfort: The wearable must achieve a comfort rating of at least 5 out of 7 on the Likert scale during user testing.
6. Battery Life: The wearable must operate for a minimum of 8 hours without charging under continuous use.
7. Universal Fit: The wearable must be adaptable for both left and right knees.
8. Impact Resistance: The wearable must withstand impacts with the other objects without effecting measuring capabilities.
9. Skin Compatibility: The materials used must not cause skin irritation under standard medical conditions (ISO 10993 compliant).
10. Hygiene: The wearable must be easily cleanable and disinfect able using standard medical-grade cleaning solutions.
11. Data Understanding: The device must present metrics in a way that is easily understandable by the user
12. Actionable Data: The metrics displayed must provide actionable insights for rehabilitation exercises.
13. Population Fit: The wearable must fit users across the 5th to 95th percentile of the population in terms of knee size and shape.
14. Data Rate: The system must have an output rate of at least 120 Hz for accurate data streaming during active guidance and data sampling.
15. Wireless Data Transfer: The wearable must transfer data wirelessly over a minimum distance of 30 meters.
16. Safety: All electronics must be insulated and according to safety standards
17. Medical guidelines: The wearable must not hinder protocol procedures.
18. Dependency: Patient must not become reliant on the systems metrics
19. The system must comply with electromagnetic noise regulations

Should have

1. Internal and External Rotation Tracking: The wearable should measure internal and external rotation with an accuracy of 1°.
2. Abduction and Adduction Tracking: The wearable should measure abduction and adduction angles with a precision of 0.2°.
3. Ease of Maintenance: Components should be designed for easy replacement or maintenance, with a maximum replacement time of 5 minutes for wearable parts.
4. Intuitive Placement: The device should be designed such that the user intuitively places the sensors in the correct position when wearing it.
5. Sensor Stability: The garment should minimize sensor displacement during movement, ensuring data accuracy.
6. Weather Resistance: The device should operate reliably in temperatures between -40°C and 85°C and resist rain or sweat.
7. Dust and Water Resistance: The wearable should achieve at least IP54 certification for dust and water resistance.
8. Telerehabilitation Support: The system should integrate with telecommunication platforms to support remote monitoring and feedback.
9. Gait Metrics: The wearable should calculate basic gait metrics, including stride length, cadence.
10. Patient Self-Questioning: The system should include a feature to question patients about their illness beliefs and mental state during rehabilitation, with customizable prompts.
11. Progress Tracking: The system should be able to provide visual representations of progress can boost motivation and adherence to rehabilitation protocols.
12. Stigma Reduction: The wearable should include aesthetic or design elements that reduce the stigma of wearing a medical device.
13. Data privacy and security: The system should consider privacy and data security

Could have

1. Active Exercise Guidance: The device could provide real-time feedback and guidance during rehabilitation exercises via haptic, auditory, or visual cues.
2. Open and Closed Kinematics Detection: The device could differentiate between open and closed kinematic chain exercises.
3. Knee Rehabilitation Versatility: The wearable could support multiple types of knee rehabilitation protocols (e.g., post-ACL surgery, osteoarthritis, etc.).
4. Patient Education: Provide information about the importance of each exercise and how it contributes to recovery, empowering patients with knowledge

Wish to have

1. Patient Self-Questioning: The system could include a feature to question patients about their illness beliefs and mental state during rehabilitation, with customizable prompts.
2. Emotion-Driven Metrics: The system could incorporate emotion recognition algorithms to adapt rehabilitation strategies based on emotional states.
3. Production Cost Efficiency: The production cost per unit should be below € 200 for mass production (>10,000 units).
4. Extended Wireless Range: The wearable could extend its wireless data transfer range to 50 meters or more to be able to play field sports with phone on the sideline.

Appendix O: HREC letter of approval

Date 24-Mar-2025
Correspondence hrec@tudelft.nl

TU Delft Delft University of Technology

[redacted]

Ethics Approval Application: A Patient-Focused Wearable for Engaging and Supported Knee Injury Recovery
Applicant: Bouwmeester, tim

Dear tim Bouwmeester,

It is a pleasure to inform you that your application mentioned above has been approved.

Thanks very much for your submission to the HREC which has been conditionally approved. Please note that this approval is subject to your ensuring that the following condition/s is/are fulfilled:

Please let your faculty's HSE Advisor check the prototype of the wearable system prior to using it for data collection.

In addition to any specific conditions or notes, the HREC provides the following standard advice to all applicants:
• In light of recent tax changes, we advise that you confirm any proposed remuneration of research subjects with your faculty contract manager before going ahead.
• Please make sure when you carry out your research that you confirm contemporary covid protocols with your faculty HSE advisor, and that ongoing covid risks and precautions are flagged in the informed consent - with particular attention to this where there are physically vulnerable (eg: elderly or with underlying conditions) participants involved.
• Our default advice is not to publish transcripts or transcript summaries, but to retain these privately for specific purposes/checking; and if they are to be made public then only if fully anonymised and the transcript/summary itself approved by participants for specific purpose.
• Where there are collaborating (including funding) partners, appropriate formal agreements including clarity on responsibilities, including data ownership, responsibilities and access, should be in place and that relevant aspects of such agreements (such as access to raw or other data) are clear in the Informed Consent.

Good luck with your research!

Sincerely,

[redacted]

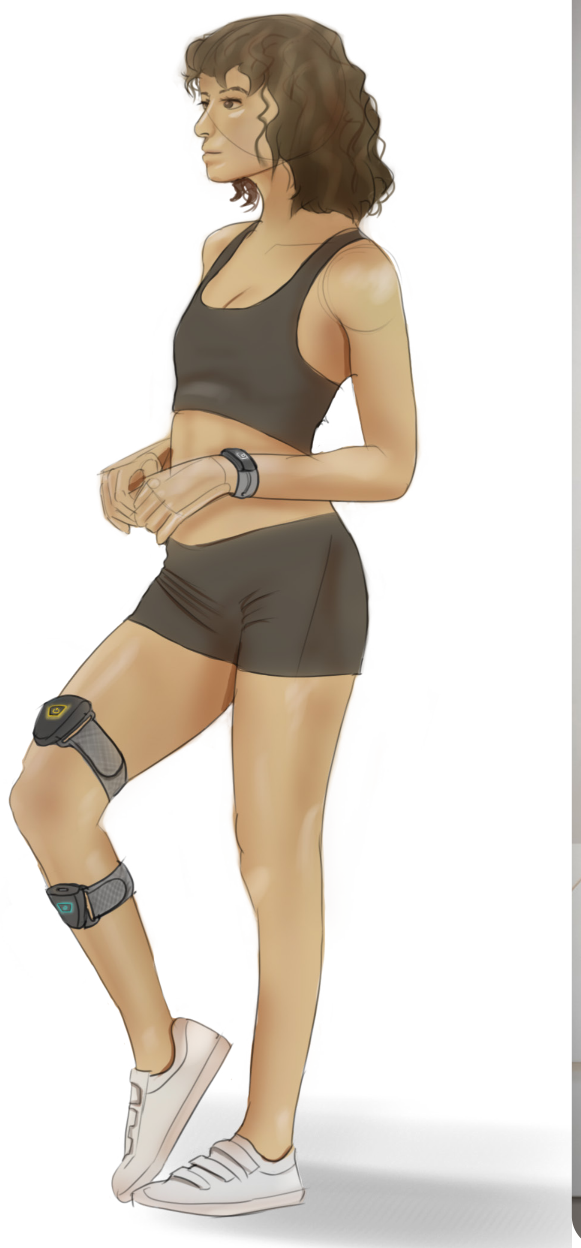
Dr. C. Shelley-Egan
Chair HREC
Faculty of Technology, Policy and Management

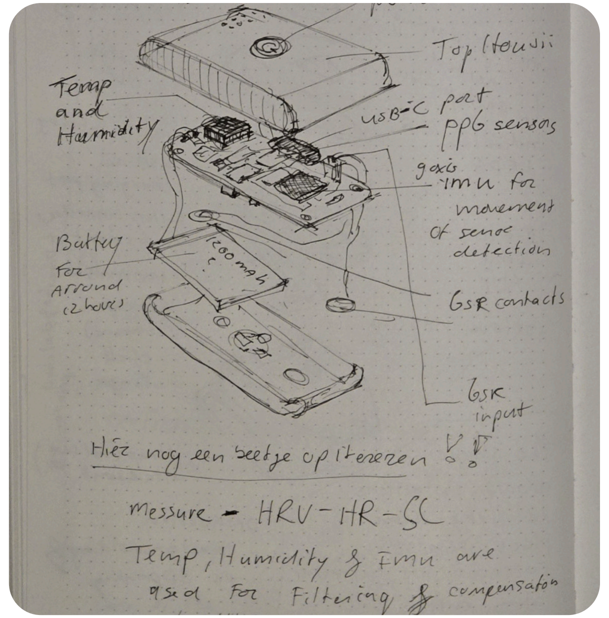
Appendix P: Battery lifetime calculations

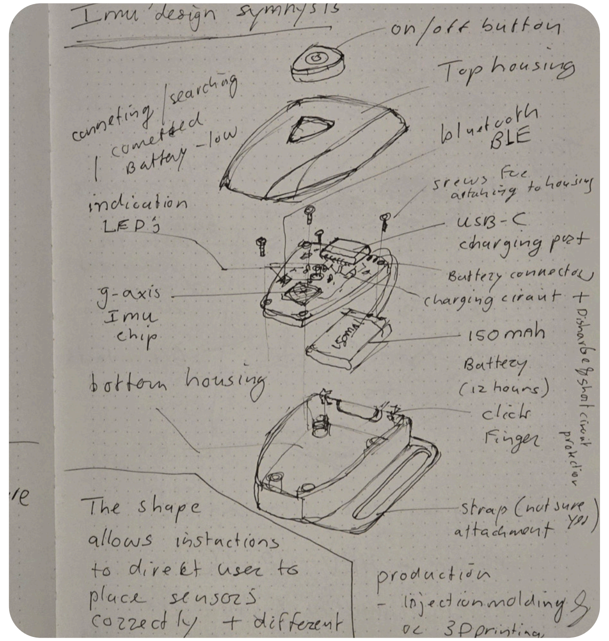
Wrist		
Component	Avg Current (mA)	Notes
IMU (6-axis)	1,5	Typical for MPU-6050 or similar
Processor (MCU)	5	Depends on architecture
BLE 5.0 Module	1,5	Assuming continuous use 1,5 mA
PPG Sensors (3x)	4,8	Assume 1.6 mA × 3 = 4,8 mA (MAX30102)
GSR Sensor	1	Custom, estimating average
Button + LEDs (2-color)	1	On occasionally, assume 1 mA average
Charging & Reg Circuit	1	Small standby draw
temp & humidity	1	small draw can be duty cycled
current draw (mA)	16,8	
Hours	11,9047619	

IMU		
Component	Avg Current (mA)	Notes
IMU (9-axis)	3	calibration and high output rate
BLE Combo	1,5	IMU inlcuded BLE cosumption
Processor	5	Depends on architecture
Button + LEDs	2	On occasionally, assume 1 mA average
Charging & Reg Circuit	1	Small standby draw
current draw (mA)	12,5	
Hours	12	

Appendix Q: Concept creation sketches







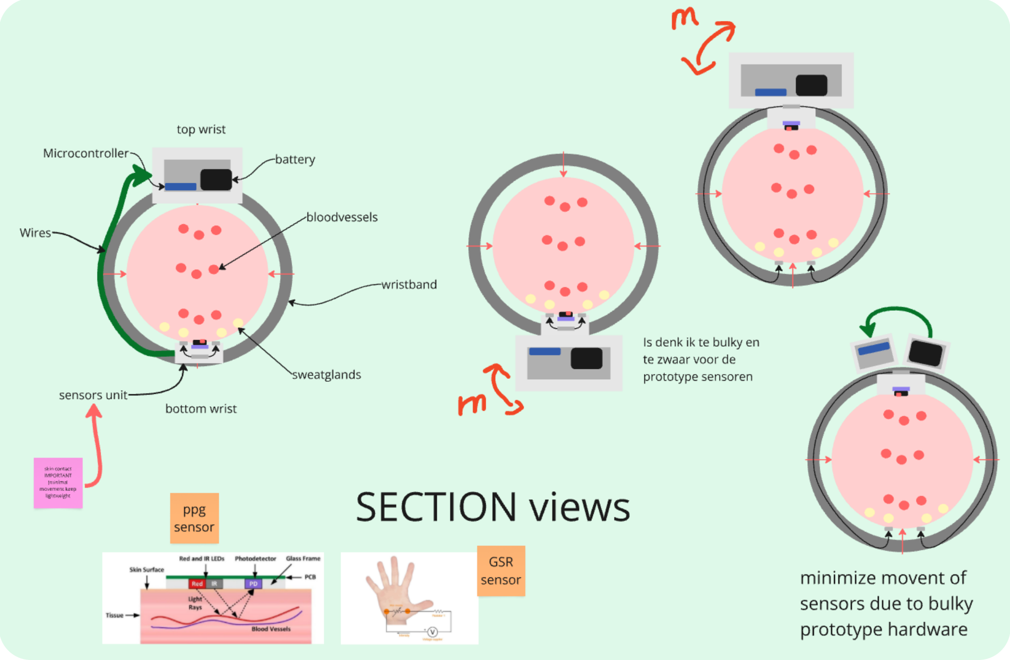
Appendix R: aditional renders

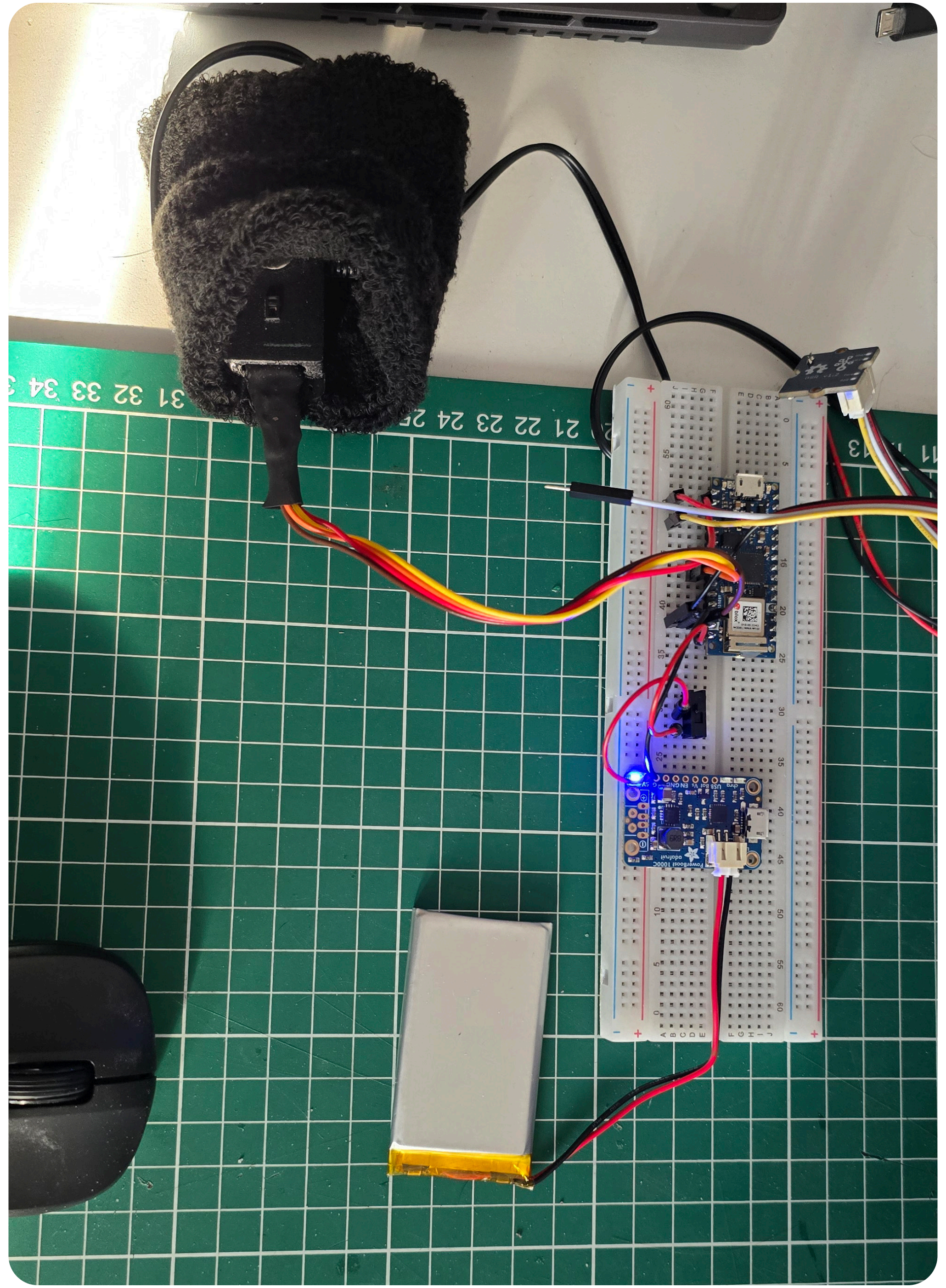
Appendix S: Prototype iterations

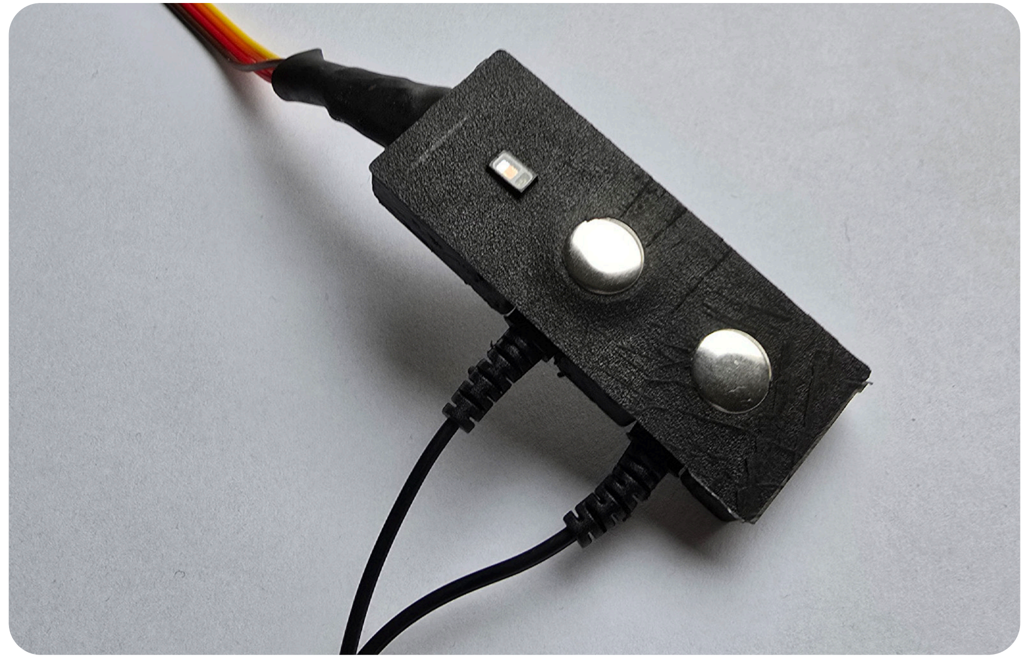
Before the final integration of the sensors was succesfull several iterations where needed to optimize the sensor placement. The prototype electronics are larger then the final implementation and placing a bluky electronic case, can result in too much intertia on the sensors. This can result in frequent loss of skin contact of the sensors producing unreliable sensor readings

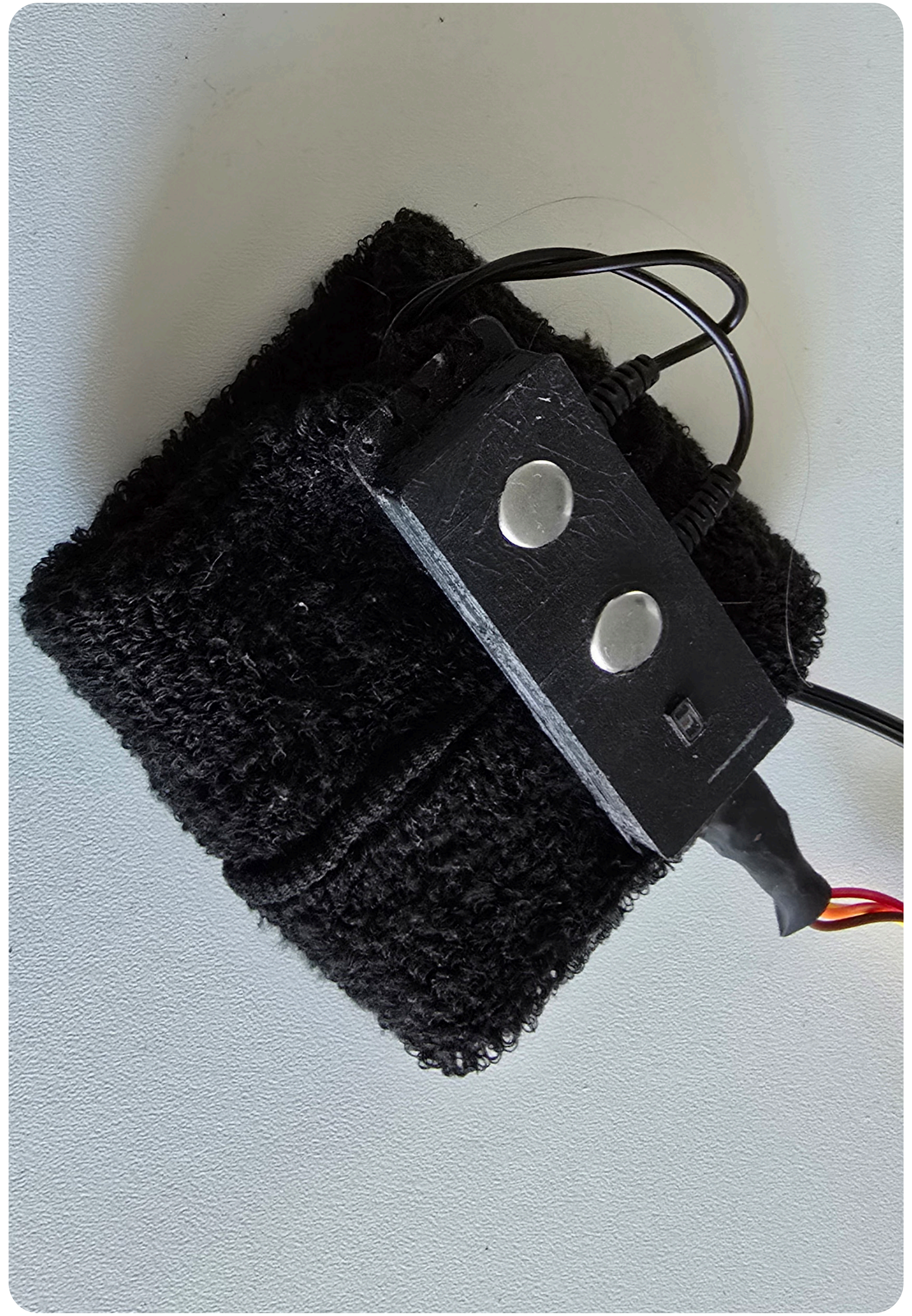
Therefore the idea is to make a seperate electronical circuit attached to the sensors for the prototype. In the first iterations a small box with the sensors was integrated into an elastic wristband. when testing this system it had issues with skin contact and missing readings due to movement therefore this iteration was discarded.

When trying to integrate the sensors into the fabric, sensor breakage occured. Furthermore some movement on the electrical pins agains the fabric or skin resulted in some noise. therefore the sensors where secured using pressing rings and a pastic case. the contactpins where potted with some resin to ensure external contact could not result in noise on the signal lines.

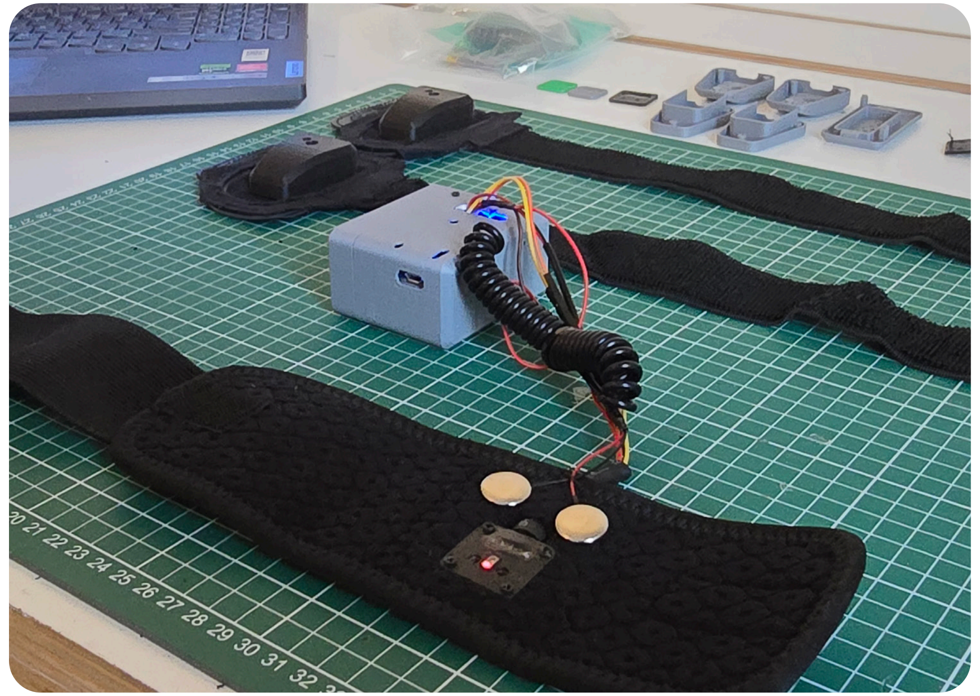


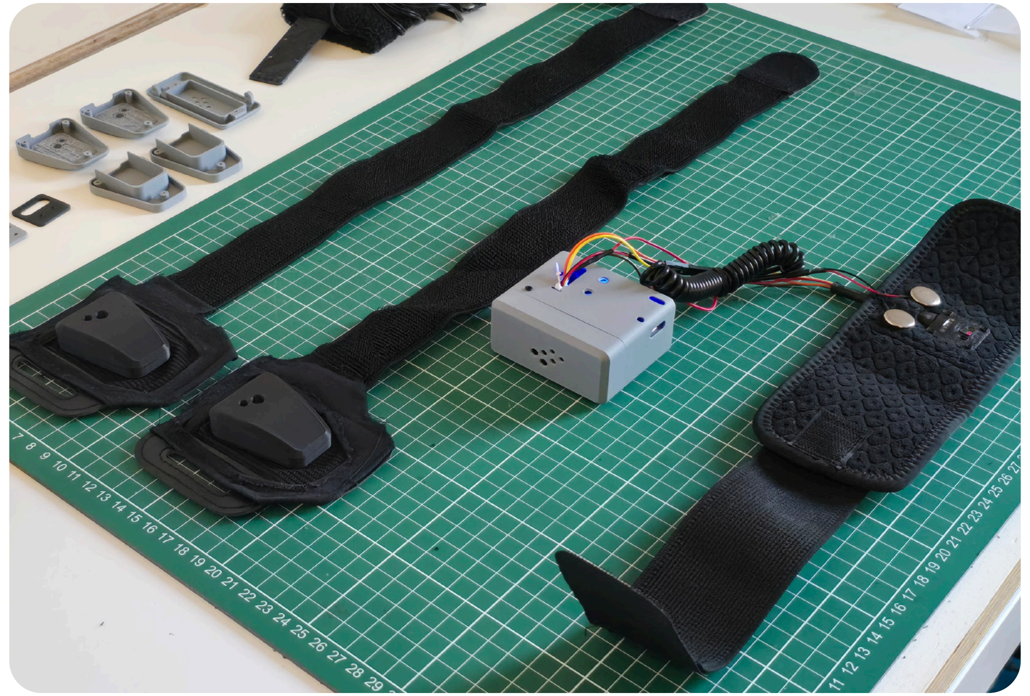


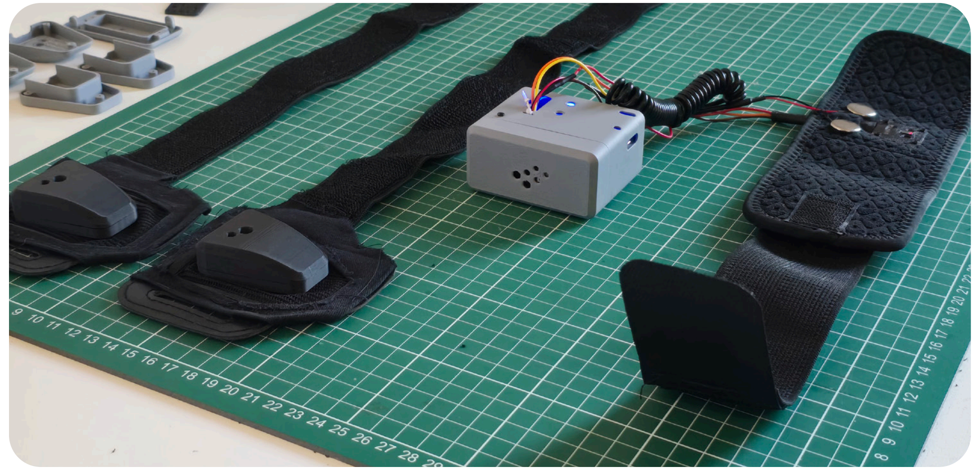


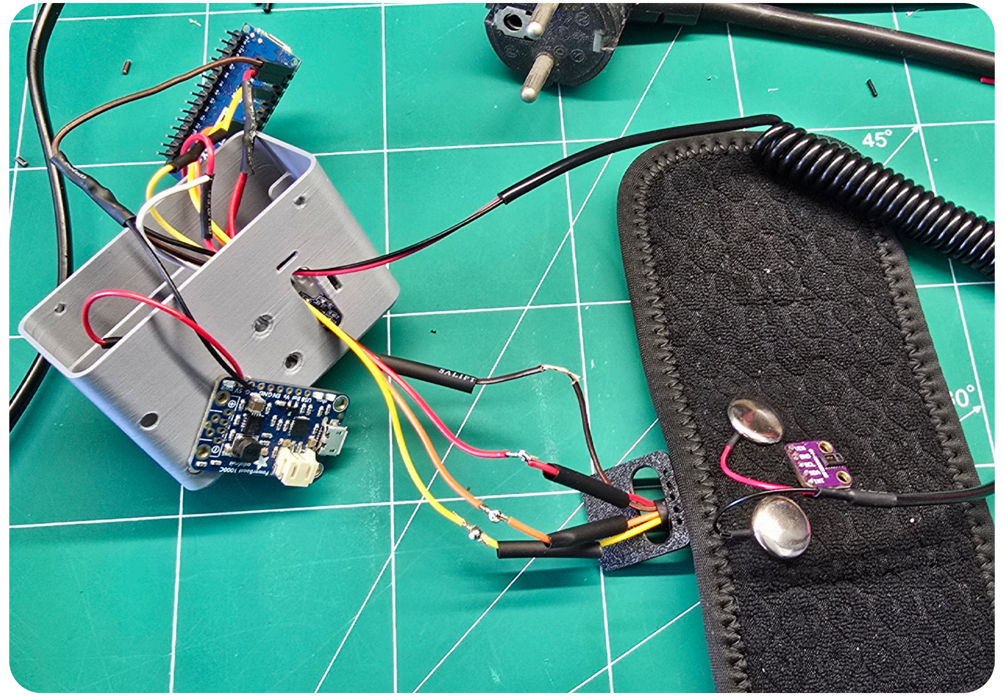


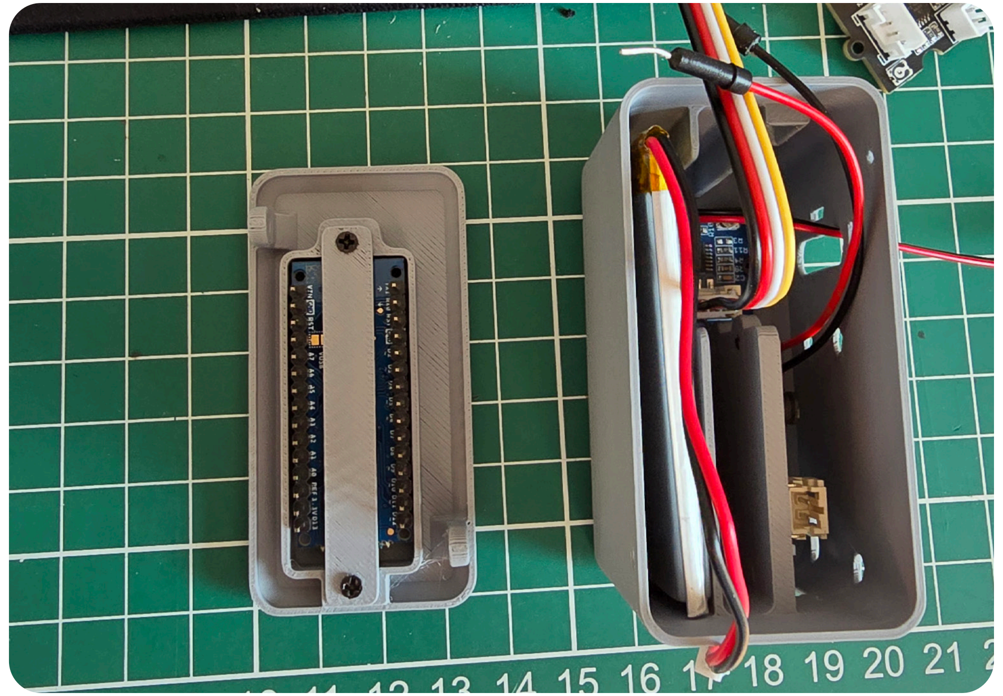
Appendix T: Functional prototype pictures

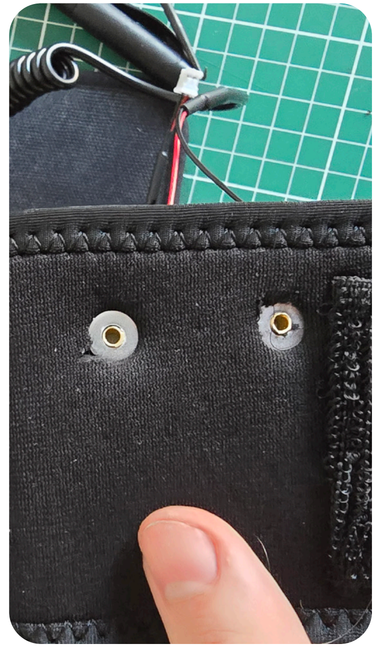


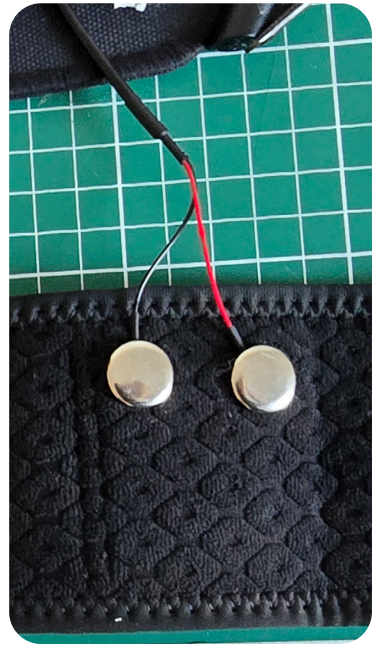


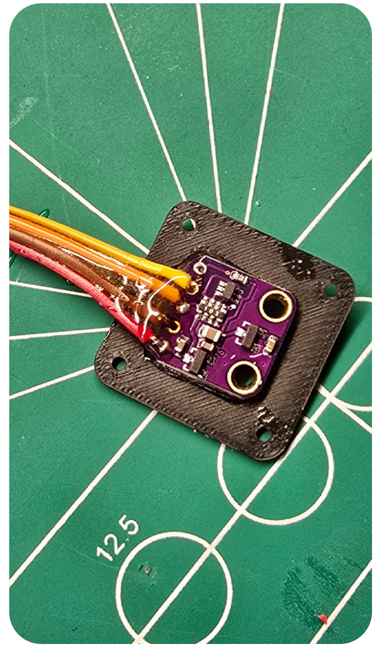




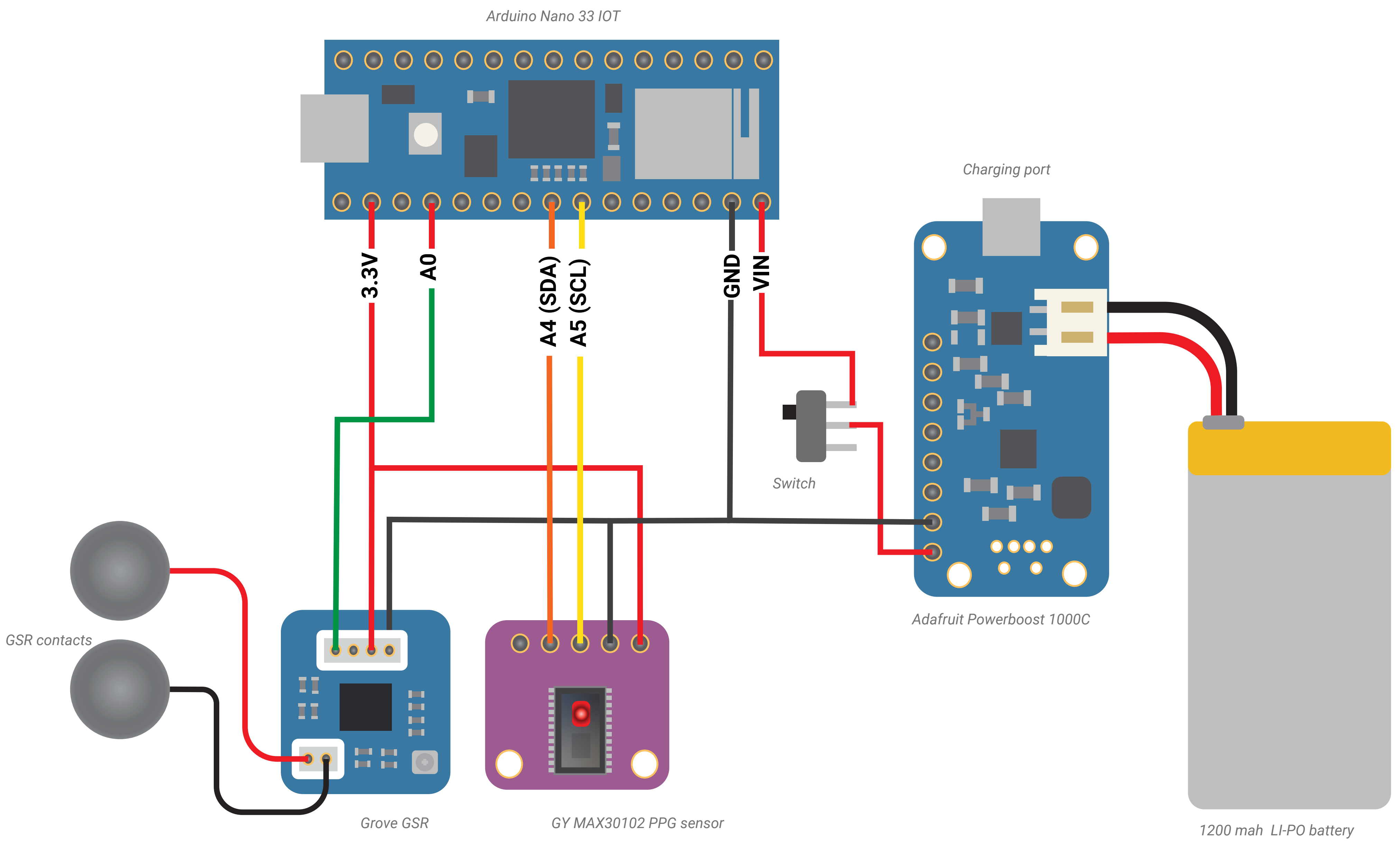








Appendix U: Electronic circuit Wristmodule prototype



Appendix V: Inform consent user test

You are being invited to participate in a research study titled titled A patient-focused wearable for an engaging and supported knee injury recovery. This study is being conducted by Tim Bouwmeester from the Technical University of Delft. This is an internal TUD MSc thesis project from the faculty Industrial design engineering
The purpose of this research is to evaluate the usability and effectiveness of Symphysis, a wearable system designed to support both physical and mental aspects of knee rehabilitation. The study will help determine if the device accurately tracks emotional arousal signals, such as stress, related to knee movements and if it is intuitive and comfortable to use
Participation in this study will take approximately 30-45 minutes to complete.
You will be asked to perform the following activities:

1. Putting on the symphysis wearable system
2. Relaxed siting while recording baseline sensor levels (5min)
3. Perform 15 squats at your own pace
4. 2 minutes rest
5. Perform 15 squats with an extra cognitive load (counting backwards)
6. Filling in a questionnaire about your experience, the usability of the device and your emotional response

Your participation is confidential. We will assign you a participant number to anonymize your data, and your identity will not be revealed in any reports or publications. All data will be stored securely in a protected database, accessible only to the student researcher and the supervision team. Any personal information collected for administrative purposes (signatures) will be deleted after the study is completed. We will not collect any personal data such as your name or IP address.
In the questionnaire the participant will be asked for your (age, gender, fitness level and how fast you experience stress).
The data collected will be used for academic purposes and will be analysed and the results will be published in TU Delft repository. The original database will be deleted after the study is complete. While every effort will be made to safeguard your data, please note that there is a small risk of data breaches. We will take the necessary precautions to minimize this risk.
Your participation in this study is completely voluntary. You may withdraw at any time. If you decide to withdraw after the test, you may request your data to be deleted until the study is finished by contacting the researcher. After this period, the data will be anonymized and cannot be linked back to you.
In this study there are certain risks involved. Therefore, read the following statements clearly and check the box accordingly to your own situation. In order to participate in this study, you have to agree with all statements.

I confirm that I am between the ages of 18 and 65.

Yes ☐ No ☐

I acknowledge that I have not experienced any injuries (mental & physical) in the past that limit my ability to move or perform physical activities (in total 2 x 15 squats) today.

Yes ☐ No ☐

I understand that incorporating cognitive tasks during physical exercise may cause temporary emotional responses, such as increased stress. I am aware of this potential risk and willingly accept it.

Yes ☐ No ☐

I understand that the wearable system is collecting data about physical response to emotional arousal and knee movement.

Yes ☐ No ☐

I agree with the demographic data that is collected in this study ((age, gender, fitness level and how fast you experience stress)

Yes ☐ No ☐

By signing this document, I confirm that I have read the informed consent document and agree to the use of my information for contribution to this research.

Signature: ______________________

Contact information:

[redacted]

Appendix W: Cost estimation

Symphysis hardware cost	amount	10.000

IMU modules (thigh and shin)

parts/processes	description	amount	cost per unit	total (10000 units)
custom PCB	PCB assembly of BLE5.0-IMU combo, processor, USB-C chariging circuit	2	€ 15,00	€ 300.000,00
thigh PCB breakoutboard	PCB manufactoring of button with indication LED's	1	€ 2,00	€ 20.000,00
Shin PCB breakoutboard	PCB manufactoring of button with indication LED's	1	€ 2,00	€ 20.000,00
150 mah lipo battery	Procurement	2	€ 2,50	€ 50.000,00
custom rubber seal	rubber pressing, vulcanisation	2	€ 0,50	€ 10.000,00
STP410160090B 1.6 x 4 (srews	Procurement	12	€ 0,05	€ 6.000,00
Bottom housing	Injection molded (ABS-PC, 40x32x7) + preprosessing	2	€ 1,10	€ 22.000,00
Top housing	Injection molded (ABS-PC, 40x32x6) + preprosessing	2	€ 1,00	€ 20.000,00
final assembly	Battery soldering, flashing PCB, assembling housing	2	€ 3,00	€ 60.000,00
Factory testing	calibration of IMU units	2	€ 2,00	€ 40.000,00
				cost for IMU modules (total/units)
			2 modules	€ 54,80
			1 module	€ 27,40

Wristmodule

parts/processes	Description	amount	cost per unit	total (10000 units)
custom PCB	PCB assembly of 3 MAX30102 PPG sensors, GSR sensor, proccesor, BLE 5.0 chip, USB-C charging circuit, Temp/humidity combo sensor, IMU	1	€ 22,00	€ 220.000,00
Bottom housing	Injection molded (ABS-PC, 35x32x7) + preprosessing	1	€ 1,30	€ 13.000,00
Top housing	Injection molded (ABS-PC, 35x32x6) + preprosessing	1	€ 1,20	€ 12.000,00
custom rubber seal	rubber pressing, vulcanisation	1	€ 0,50	€ 5.000,00
STP410160090B 1.6 x 4 (srews)	Procurement	2	€ 0,03	€ 600,00
STP410160090B 1.6 x 2 (srews)	Procurement	4	€ 0,05	€ 2.000,00
200 mah lipo battery	Procurement	1	€ 3,00	€ 30.000,00
18 mm attachment inserts	Procurement	4	€ 0,50	€ 20.000,00
final assembly	Battery soldering, flashing PCB, assembling housing	1	€ 3,00	€ 30.000,00
Factory testing	testing functionality of the physiological metrics and IMU calibartion	1	€ 3,00	€ 30.000,00
				cost for wrist module (total/units)
				€ 36,26

straps

parts/processes	description	amount	cost per unit	total (10000 units)
18 mm smarthwatch straps	procurement	1	€ 1,50	€ 15.000,00
elastic band 45 mm	procurement, + cutting, price per meter	2	€ 1,20	€ 24.000,00
velcro piece	procurement + cutting, price per meter	0,1	€ 0,80	€ 800,00
neopreen fabric	procurement + cutting, price per m^2	0,02	€ 20,00	€ 4.000,00
meshfabric	procurement + cutting, price per m^2	0,008	€ 10,00	€ 800,00
plastic guard	waterjetting + preprocessing	2	€ 0,15	€ 3.000,00
5 mm elastic band	procurement + cutting, price per meter	0,1	€ 0,60	€ 600,00
assembly	sewing the parts together	2	€ 4,00	€ 80.000,00
				cost for straps
				€ 12,82

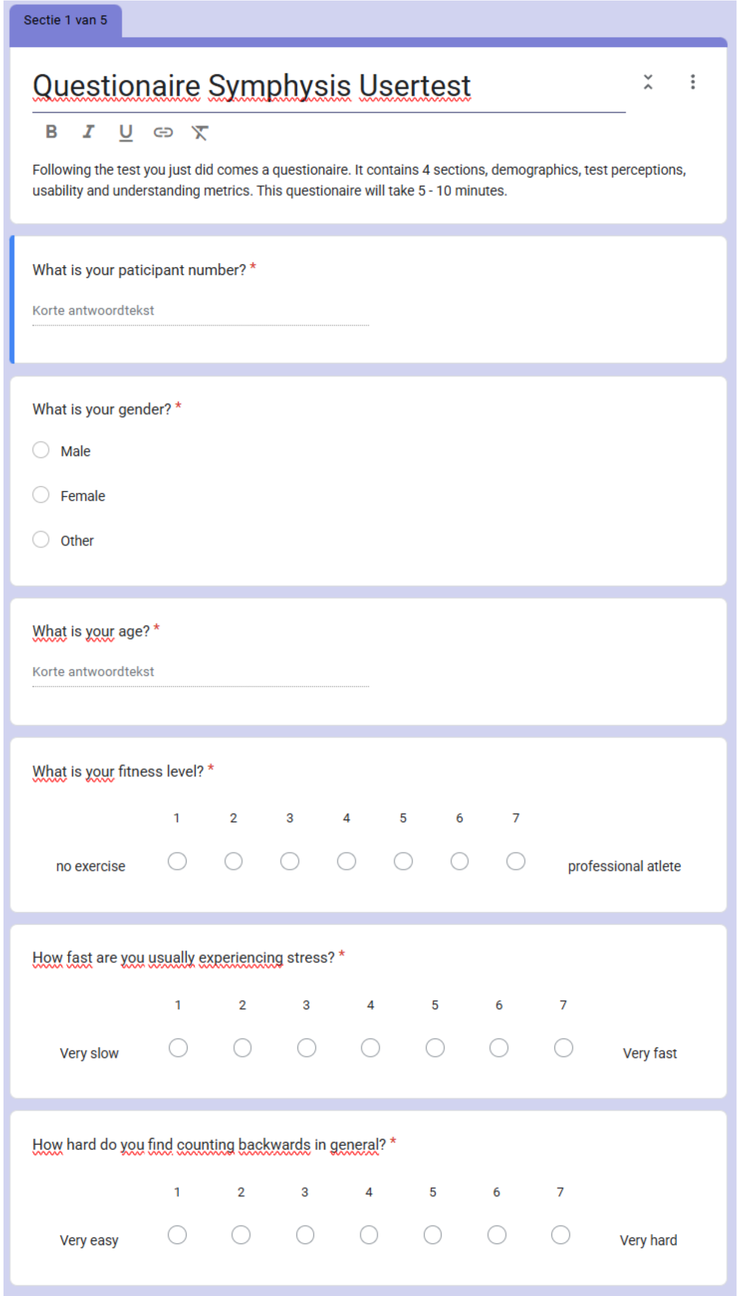
Precurement & bag

parts/processes	description	amount	cost per unit	total (10000 units)
USB-C charger block with 3 ports	Procurement	1	€ 2,50	€ 25.000,00
USB-C cable 20cm	Procurement	3	€ 0,40	€ 12.000,00
headphone hardcase	Procurement	1	€ 1,50	€ 15.000,00
custom foamcut	Foamcutting	1	€ 0,70	€ 7.000,00
logo stickers	printed stickers	2	€ 0,10	€ 2.000,00
			Cost	€ 6,10

Symphysis hardware cost	production/procurement cost
Thigh module	€ 27,30
Shin module	€ 27,30
Wrist Module	€ 36,20
straps	€ 12,82
charger + bag	€ 6,10
packaging + overhead	€ 6,00
Total	€ 115,72

investments	cost
Alumunium Injection mold 1 (bottom IMU)	6000
Alumunium Injection mold 2 (top IMU)	6000
Alumunium Injection mold 3 (bottom Wrist)	6500
Alumunium Injection mold 4 (bottom Wrist)	6500

Appendix X: Questionaire usertest


Sectie 1 van 5

Questionaire Symphysis Usertest

Following the test you just did comes a questionaire. It contains 4 sections, demographics, test perceptions, usability and understanding metrics. This questionaire will take 5 - 10 minutes.

What is your paticipant number? *

Korte antwoordtekst

What is your gender? *

- Male
- Female
- Other

What is your age? *

Korte antwoordtekst

What is your fitness level? *

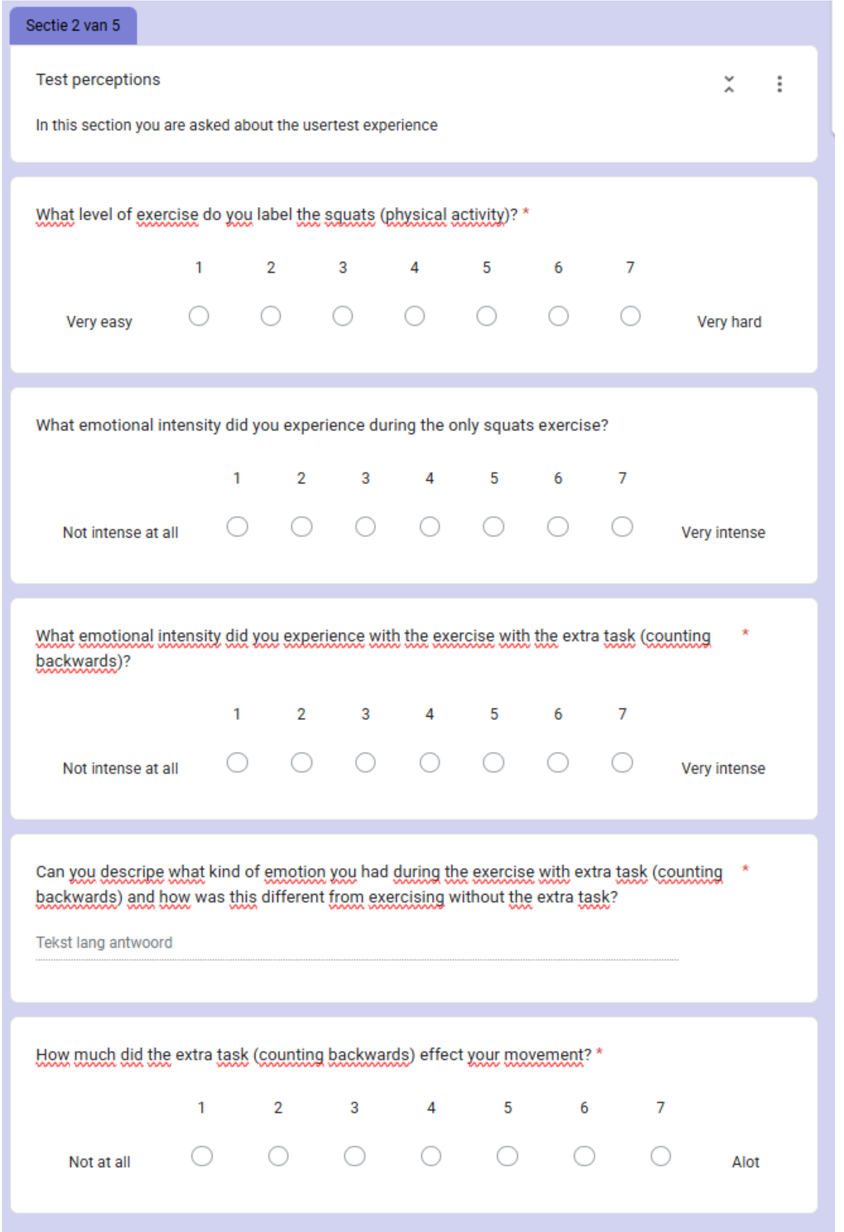
no exercise 1 2 3 4 5 6 7 professional atlete

How fast are you usually experiencing stress? *

Very slow 1 2 3 4 5 6 7 Very fast

How hard do you find counting backwards in general? *

Very easy 1 2 3 4 5 6 7 Very hard


Sectie 2 van 5

Test perceptions

In this section you are asked about the usertest experience

What level of exercise do you label the squats (physical activity)? *

Very easy 1 2 3 4 5 6 7 Very hard

What emotional intensity did you experience during the only squats exercise?

Not intense at all 1 2 3 4 5 6 7 Very intense

What emotional intensity did you experience with the exercise with the extra task (counting backwards)? *

Not intense at all 1 2 3 4 5 6 7 Very intense

Can you descripe what kind of emotion you had during the exercise with extra task (counting backwards) and how was this different from exercising without the extra task? *

Tekst lang antwoord

How much did the extra task (counting backwards) effect your movement? *

Not at all 1 2 3 4 5 6 7 Alot

Sectie 3 van 5

Usability

In this section you are asked about the usability of symphysis system

How intutive was it to place the wearable system using the instructions? *

	1	2	3	4	5	6	7	
not intuitive at all	○	○	○	○	○	○	○	Very intuitive

How comfortable was it to wear the wearable system? *

	1	2	3	4	5	6	7	
Not comfortable	○	○	○	○	○	○	○	Very comfortable

Sectie 4 van 5

Understanding of metrics

The purpose of this section is to gather your thoughts on the metrics I plan to present in the Symphysis application. I want to ensure these metrics are meaningful, easy to understand, and genuinely useful to patients. With your feedback, I can make these insights clearer and more relevant.

Overview of daily activity

After seeing your knee load and body stress data in the overview above, how would you describe your current state? and what would you do? *

Tekst lang antwoord

Knee strain reflects the amount of movement throughout the day, recovery indicates the percentage of time the body is in a resting state, and emotional load represents the level of stress, anxiety, and pain responses experienced by the body. With this explanation, would you now understand how to interpret the overview? *

- ○ Yes
- ○ No

Given the definitions of each metric—knee strain as daily movement, recovery as the percentage of time the body is at rest, and emotional load as the body's stress, anxiety, and pain responses—how would you interpret the overall data? *

Tekst lang antwoord

HRV (heart rate variability) reflects how your body is recovering and responding to stress. Higher HRV usually means better recovery or readiness. I use this to estimate how prepared your body is for physical activity. Did you know about HRV before? *

- ○ Yes
- ○ No

How clear was the description of HRV in the previous question? *

	1	2	3	4	5	6	7	
not clear	○	○	○	○	○	○	○	very clear

SC (Skin conductance) reflects changes in skin conductivity linked to emotional or physiological arousal (stress, pain or excitement). A sudden increase in SC can indicate strong emotional response. We use this to detect how emotions may influence your movement patterns. Did you know about this metric? *

- ○ Yes
- ○ No

How clear was the description of SC in the previous question? *

	1	2	3	4	5	6	7	
not clear	○	○	○	○	○	○	○	very clear

"Jerk" is used to describe the smoothness of movement. A higher Jerk can indicate motor control issues or stress. Did you know about this metric? *

- ○ Yes
- ○ No

How clear was the description of "jerk" in the previous question? *

	1	2	3	4	5	6	7	
not clear	○	○	○	○	○	○	○	Very clear

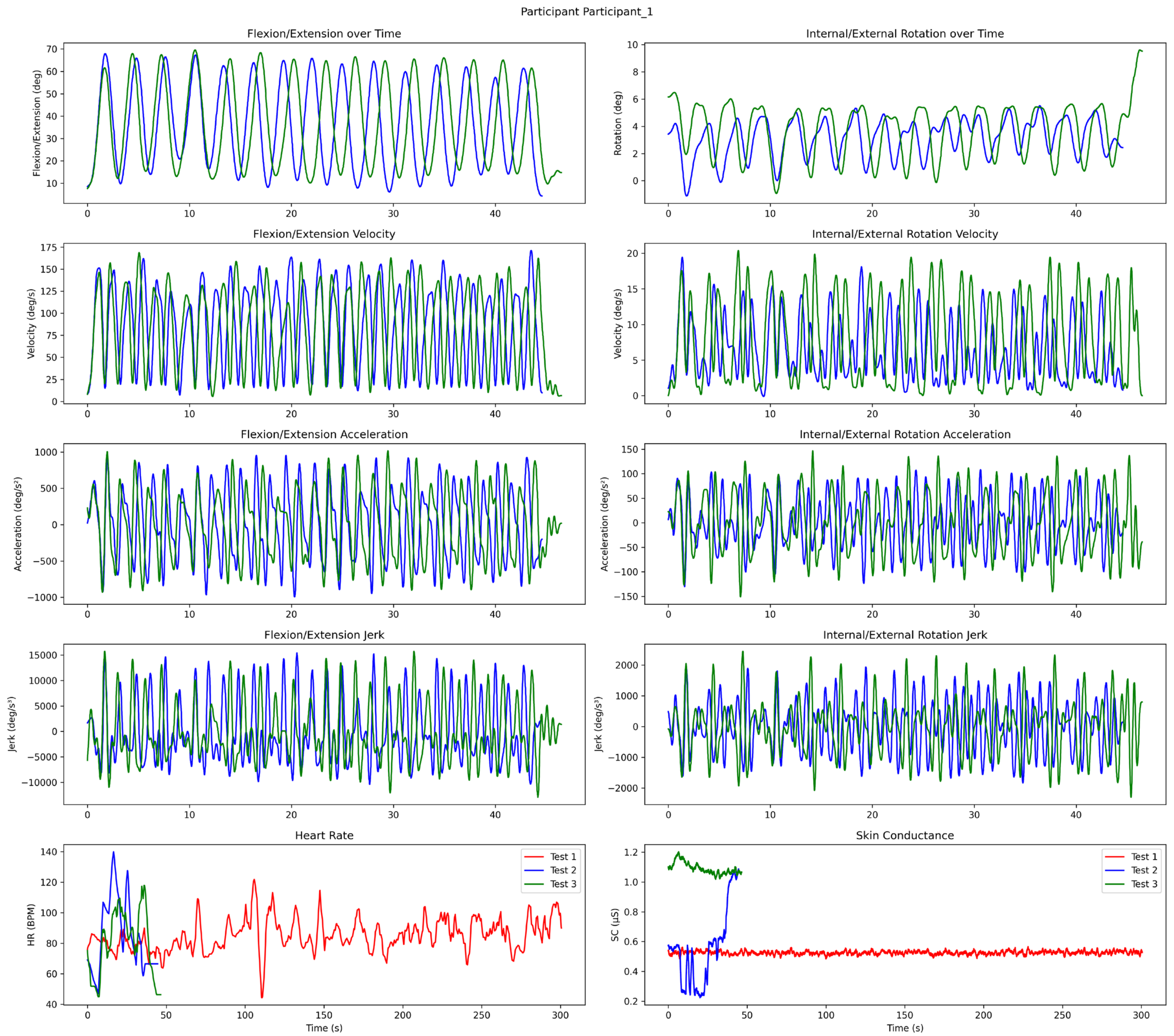
An important metric in knee rehabilation is ROM, do you know what ROM means? *

- ○ Yes
- ○ No

ROM stands for range of motion. In knee rehabilitation this stands for the angle of the knee. A common goal is to reach targets to increase ROM to a range of -5 to 130 ° . How clear was this description of ROM? *

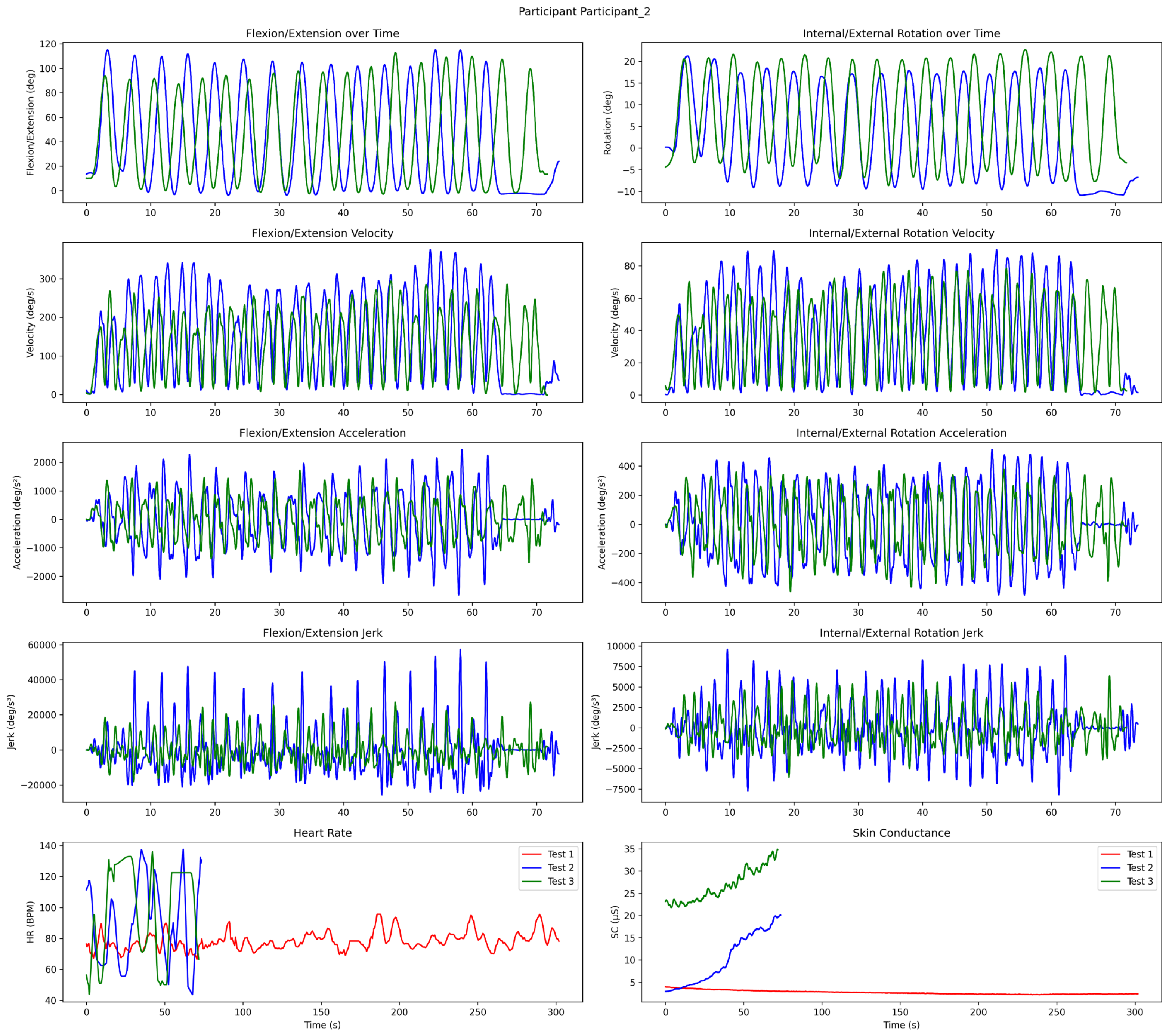
	1	2	3	4	5	6	7	
not clear	○	○	○	○	○	○	○	very clear

Appendix Y: Sensor data results



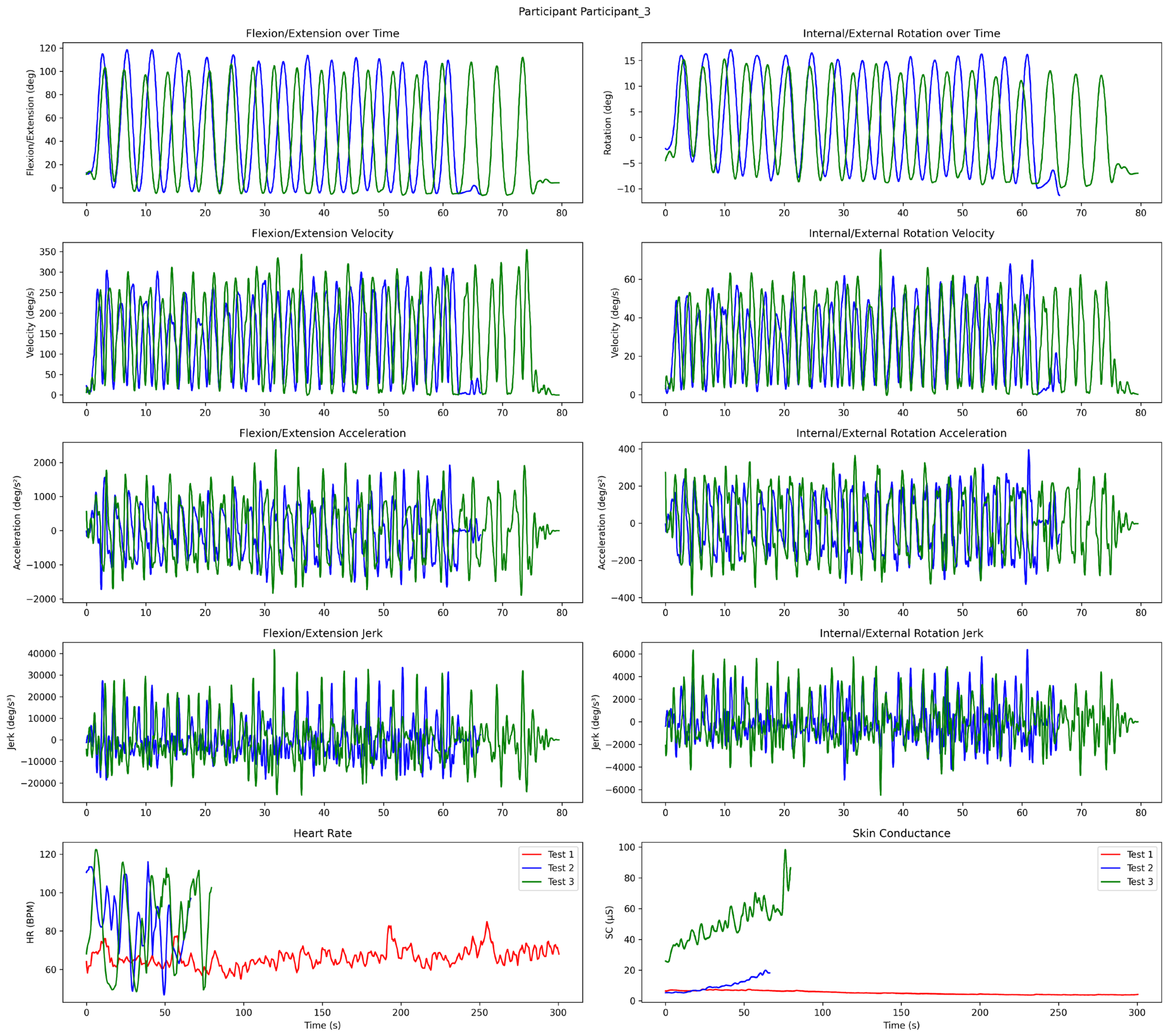
Participant: Participant_1

Metric	Test 1	Test 2	Test 3
Time (s)	300.54	44.57	46.47
Max Flexion/Extention (deg)	78.59	67.93	69.54
Min Flexion/Extention (deg)	77.56	4.30	7.61
Max Internal/External Rotation (deg)	6.13	5.51	9.60
Min Internal/External Rotation (deg)	4.07	-1.12	-0.93
Avg HR (BPM)	85.13	84.47	79.55
Max HR (BPM)	121.71	139.87	117.85
Min HR (BPM)	44.38	46.90	44.95
Avg SC (µS)	0.53	0.55	1.09
Max SC (µS)	0.57	1.09	1.20
Min SC (µS)	0.48	0.22	1.02
Avg Velocity Flexion (deg/s)	0.04	87.98	83.71
Max Velocity Flexion (deg/s)	1.10	171.11	168.69
Avg Acceleration Flexion (deg/s²)	0.00	-1.45	0.92
Max Acceleration Flexion (deg/s²)	7.73	952.75	1014.54
Avg Jerk Flexion (deg/s³)	-0.02	-74.23	-58.88
Max Jerk Flexion (deg/s³)	98.45	15399.53	15715.29
Avg Velocity Rotation (deg/s)	0.06	6.68	8.09
Max Velocity Rotation (deg/s)	4.15	19.44	20.39
Avg Acceleration Rotation (deg/s²)	-0.00	-0.00	0.10
Max Acceleration Rotation (deg/s²)	29.54	108.10	146.36
Avg Jerk Rotation (deg/s³)	-0.13	-6.11	-3.77
Max Jerk Rotation (deg/s³)	427.88	1937.28	2448.94
HRV RMSDD (ms)	0.39	0.50	0.56
HRV SDNN (ms)	100.14	210.96	244.30



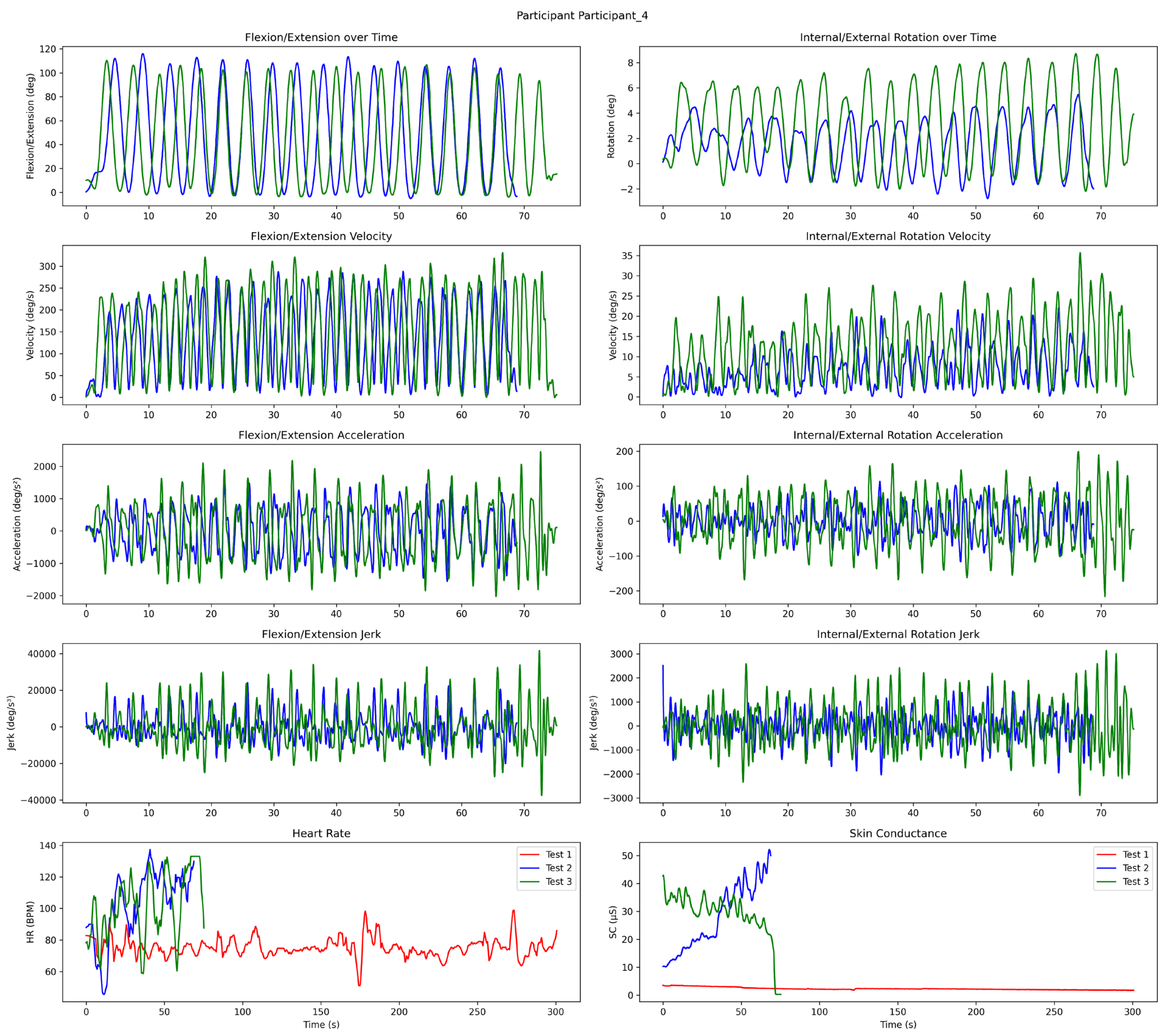
Participant: Participant_2

Metric	Test 1	Test 2	Test 3
Time (s)	301.88	73.49	71.69
Max Flexion/Extention (deg)	109.97	115.20	112.86
Min Flexion/Extention (deg)	104.76	-3.85	-2.93
Max Internal/External Rotation (deg)	8.19	21.27	22.69
Min Internal/External Rotation (deg)	-0.51	-10.89	-8.67
Avg HR (BPM)	78.40	89.04	98.32
Max HR (BPM)	95.69	137.69	136.15
Min HR (BPM)	66.45	43.65	43.93
Avg SC (µS)	2.70	10.05	26.67
Max SC (µS)	3.97	20.16	34.93
Min SC (µS)	2.20	2.92	21.81
Avg Velocity Flexion (deg/s)	0.05	151.21	135.10
Max Velocity Flexion (deg/s)	6.58	374.85	293.29
Avg Acceleration Flexion (deg/s²)	0.00	1.58	1.09
Max Acceleration Flexion (deg/s²)	23.58	2450.72	1720.49
Avg Jerk Flexion (deg/s³)	-0.01	-55.68	-156.53
Max Jerk Flexion (deg/s³)	206.41	57318.78	27130.17
Avg Velocity Rotation (deg/s)	0.09	36.68	37.10
Max Velocity Rotation (deg/s)	15.76	90.09	78.58
Avg Acceleration Rotation (deg/s²)	-0.00	0.03	0.08
Max Acceleration Rotation (deg/s²)	83.25	514.37	377.73
Avg Jerk Rotation (deg/s³)	-0.01	-16.98	-42.99
Max Jerk Rotation (deg/s³)	580.51	9590.42	6368.05
HRV RMSDD (ms)	0.15	0.59	0.56
HRV SDNN (ms)	53.39	244.80	274.93



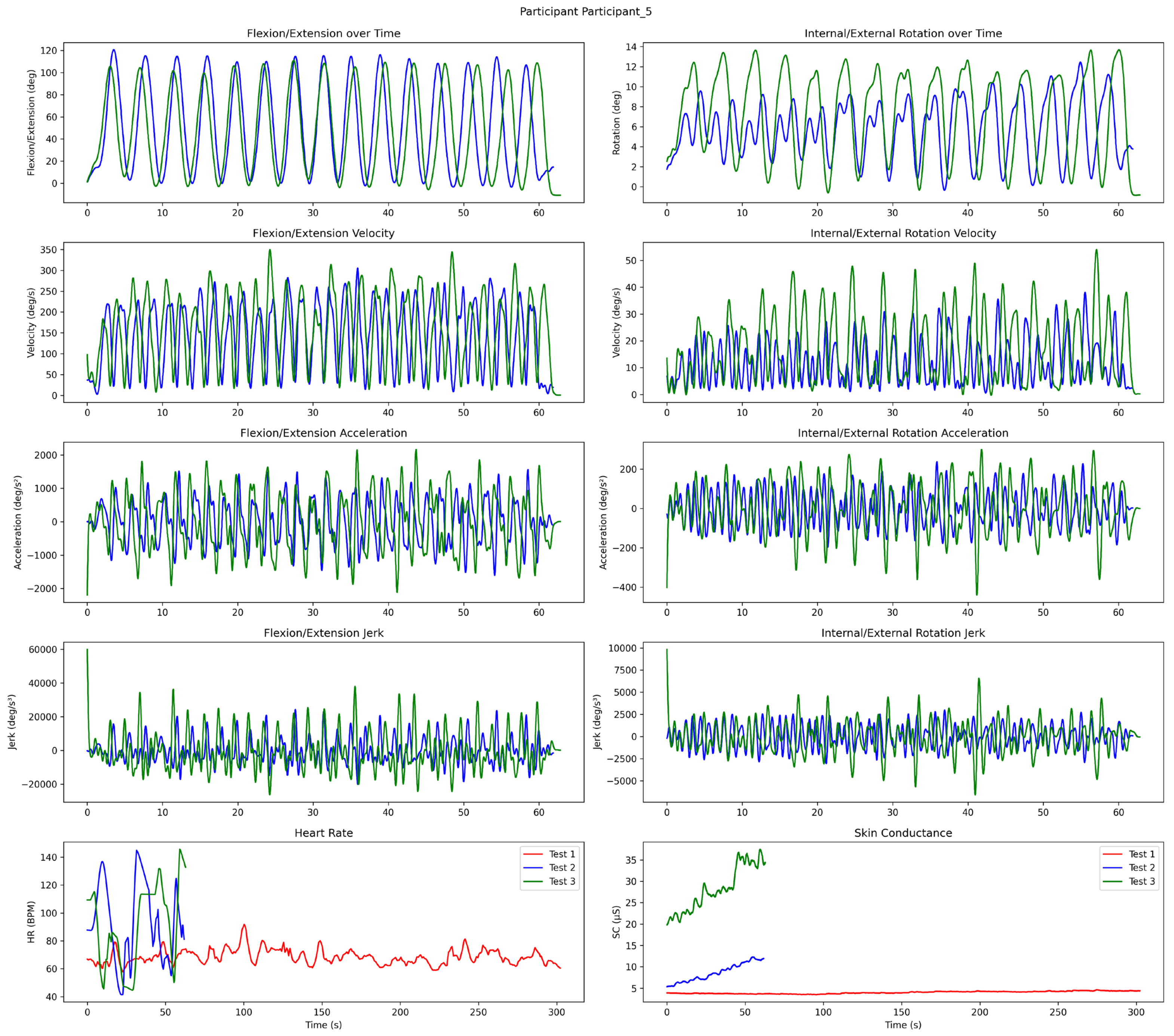
Participant: Participant_3

Metric	Test 1	Test 2	Test 3
Time (s)	300.46	66.32	79.51
Max Flexion/Extention (deg)	69.70	118.47	111.94
Min Flexion/Extention (deg)	69.12	-5.65	-6.50
Max Internal/External Rotation (deg)	-0.79	17.05	15.23
Min Internal/External Rotation (deg)	-1.52	-11.29	-9.80
Avg HR (BPM)	66.26	84.90	83.68
Max HR (BPM)	84.84	116.09	122.45
Min HR (BPM)	54.99	46.64	48.42
Avg SC (µS)	5.17	9.97	50.88
Max SC (µS)	7.53	19.86	98.42
Min SC (µS)	3.77	5.16	25.16
Avg Velocity Flexion (deg/s)	0.02	144.74	140.87
Max Velocity Flexion (deg/s)	0.55	311.49	354.43
Avg Acceleration Flexion (deg/s²)	0.00	-0.94	2.07
Max Acceleration Flexion (deg/s²)	2.07	1918.92	2374.49
Avg Jerk Flexion (deg/s³)	-0.02	-133.36	-162.51
Max Jerk Flexion (deg/s³)	20.14	33478.01	41789.30
Avg Velocity Rotation (deg/s)	0.02	29.72	28.42
Max Velocity Rotation (deg/s)	0.29	70.01	75.35
Avg Acceleration Rotation (deg/s²)	-0.00	-0.01	0.47
Max Acceleration Rotation (deg/s²)	2.24	395.91	364.16
Avg Jerk Rotation (deg/s³)	-0.02	-29.61	-37.34
Max Jerk Rotation (deg/s³)	33.40	6374.26	6316.31
HRV RMSDD (ms)	0.21	0.57	0.55
HRV SDNN (ms)	62.50	177.24	221.58



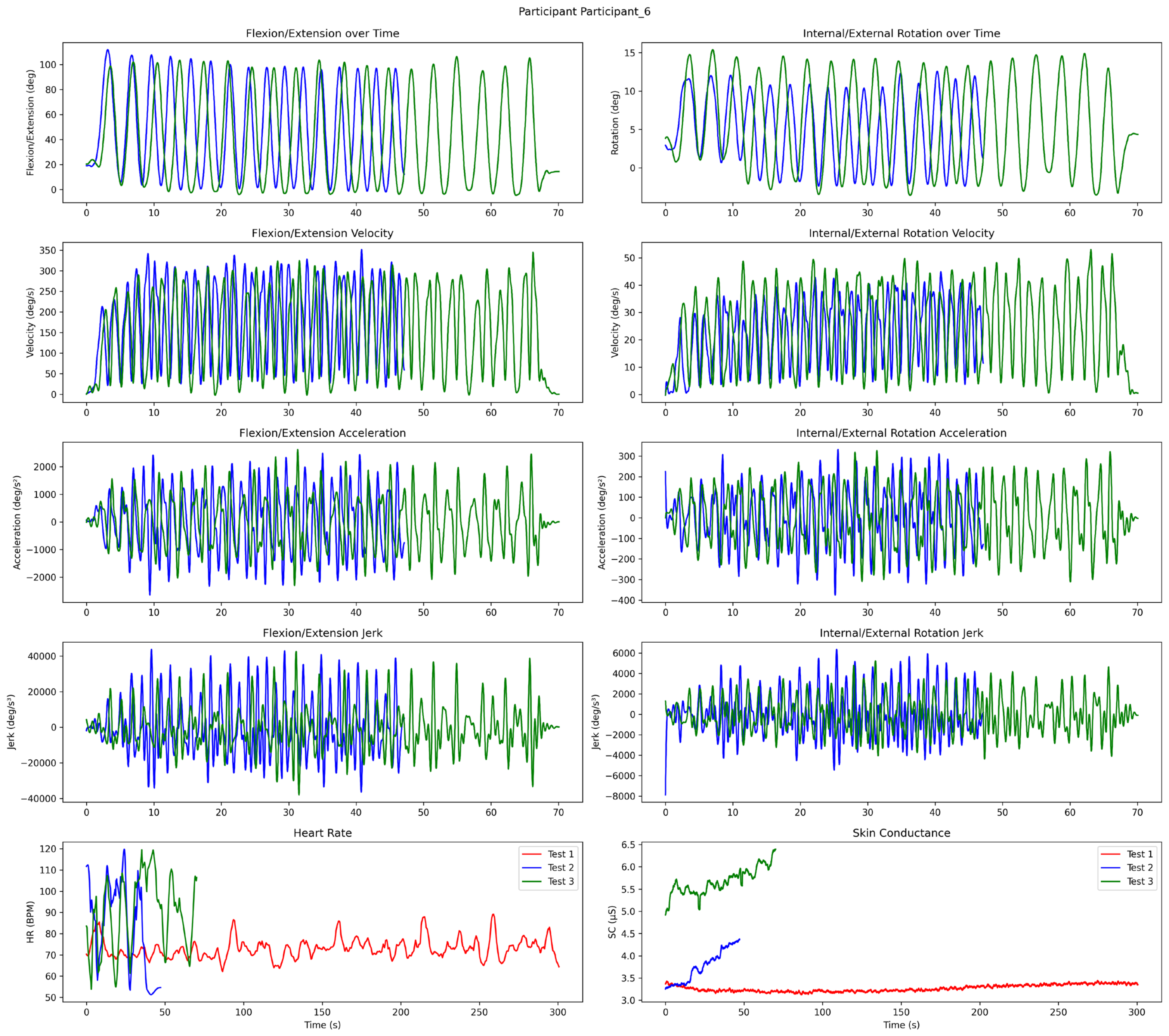
Participant: Participant_4

Metric	Test 1	Test 2	Test 3
Time (s)	300.70	68.82	75.21
Max Flexion/Extention (deg)	99.19	116.02	110.23
Min Flexion/Extention (deg)	97.53	-5.20	-4.07
Max Internal/External Rotation (deg)	-3.73	5.47	8.71
Min Internal/External Rotation (deg)	-5.51	-2.76	-2.19
Avg HR (BPM)	75.21	102.89	102.41
Max HR (BPM)	98.93	137.34	133.04
Min HR (BPM)	50.98	45.43	58.66
Avg SC (µS)	2.34	27.92	28.98
Max SC (µS)	3.59	52.12	42.95
Min SC (µS)	1.76	10.17	0.29
Avg Velocity Flexion (deg/s)	0.05	140.66	150.65
Max Velocity Flexion (deg/s)	4.83	288.48	331.14
Avg Acceleration Flexion (deg/s²)	0.00	-4.09	-0.25
Max Acceleration Flexion (deg/s²)	20.42	1511.94	2455.19
Avg Jerk Flexion (deg/s³)	-0.05	-99.15	-129.56
Max Jerk Flexion (deg/s³)	446.39	25407.91	41640.91
Avg Velocity Rotation (deg/s)	0.05	6.96	12.33
Max Velocity Rotation (deg/s)	1.99	22.07	35.72
Avg Acceleration Rotation (deg/s²)	0.00	-0.07	-0.01
Max Acceleration Rotation (deg/s²)	12.61	113.57	198.82
Avg Jerk Rotation (deg/s³)	0.03	-5.53	-11.51
Max Jerk Rotation (deg/s³)	196.28	2514.28	3135.10
HRV RMSDD (ms)	0.25	0.45	0.55
HRV SDNN (ms)	62.18	207.06	156.88



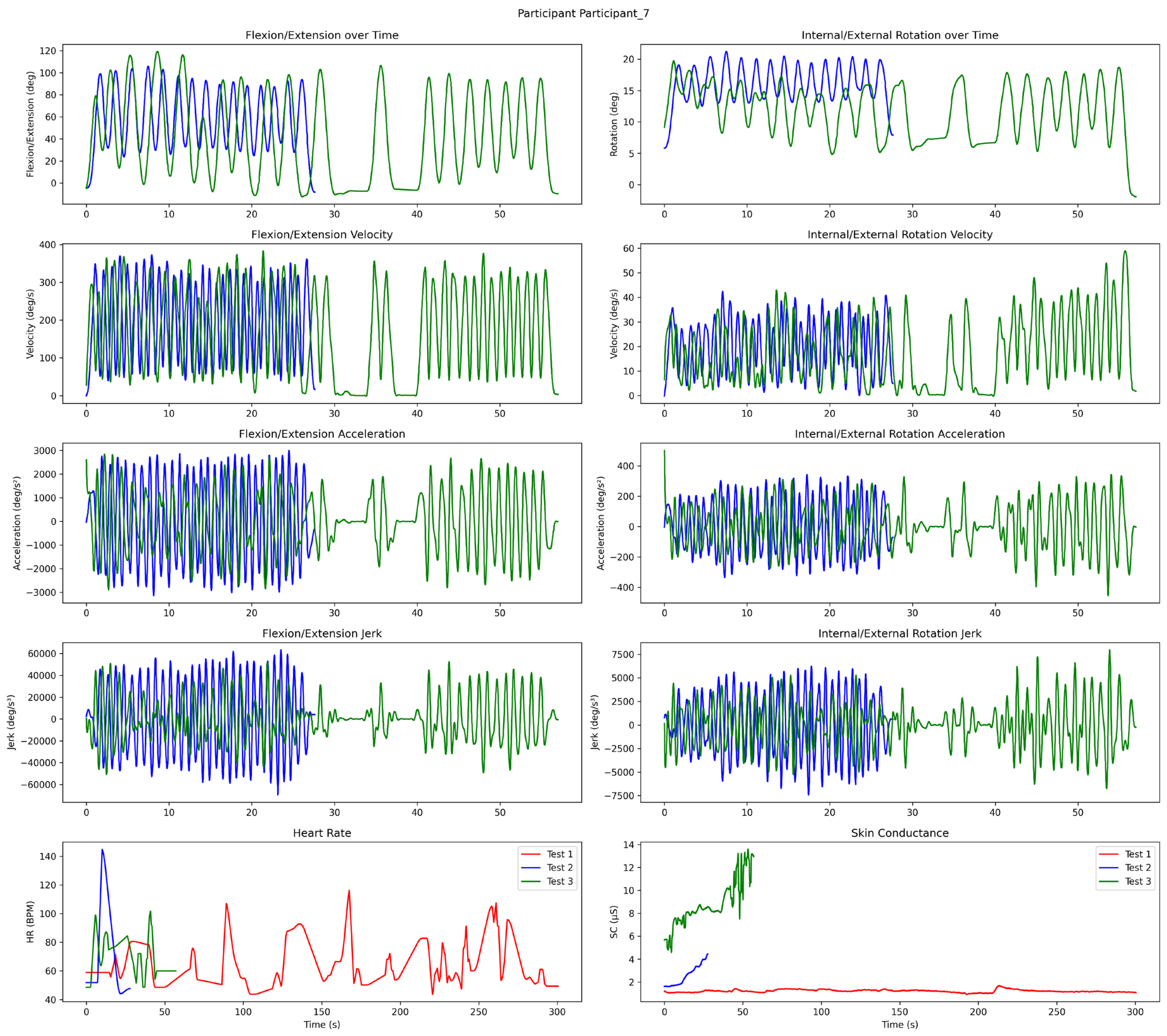
Participant: Participant_5

Metric	Test 1	Test 2	Test 3
Time (s)	302.27	61.89	62.83
Max Flexion/Extention (deg)	103.50	120.61	111.01
Min Flexion/Extention (deg)	103.07	-3.60	-10.98
Max Internal/External Rotation (deg)	5.46	12.45	13.68
Min Internal/External Rotation (deg)	4.36	-0.35	-0.85
Avg HR (BPM)	68.57	93.01	90.99
Max HR (BPM)	91.72	144.88	145.67
Min HR (BPM)	57.80	41.38	44.60
Avg SC (µS)	3.99	8.63	28.19
Max SC (µS)	4.64	12.32	37.50
Min SC (µS)	3.47	5.33	19.75
Avg Velocity Flexion (deg/s)	0.03	142.94	157.52
Max Velocity Flexion (deg/s)	0.12	305.78	349.79
Avg Acceleration Flexion (deg/s²)	-0.00	-2.16	-8.71
Max Acceleration Flexion (deg/s²)	0.79	1557.18	2160.81
Avg Jerk Flexion (deg/s³)	-0.03	-227.31	-176.44
Max Jerk Flexion (deg/s³)	14.21	24241.94	60016.23
Avg Velocity Rotation (deg/s)	0.07	12.23	17.41
Max Velocity Rotation (deg/s)	0.98	38.07	53.98
Avg Acceleration Rotation (deg/s²)	-0.00	-1.03	-0.55
Max Acceleration Rotation (deg/s²)	5.76	236.87	299.53
Avg Jerk Rotation (deg/s³)	-0.07	-19.87	-20.58
Max Jerk Rotation (deg/s³)	54.39	2983.03	9836.58
HRV RMSDD (ms)	0.18	0.64	0.64
HRV SDNN (ms)	63.23	274.20	302.74



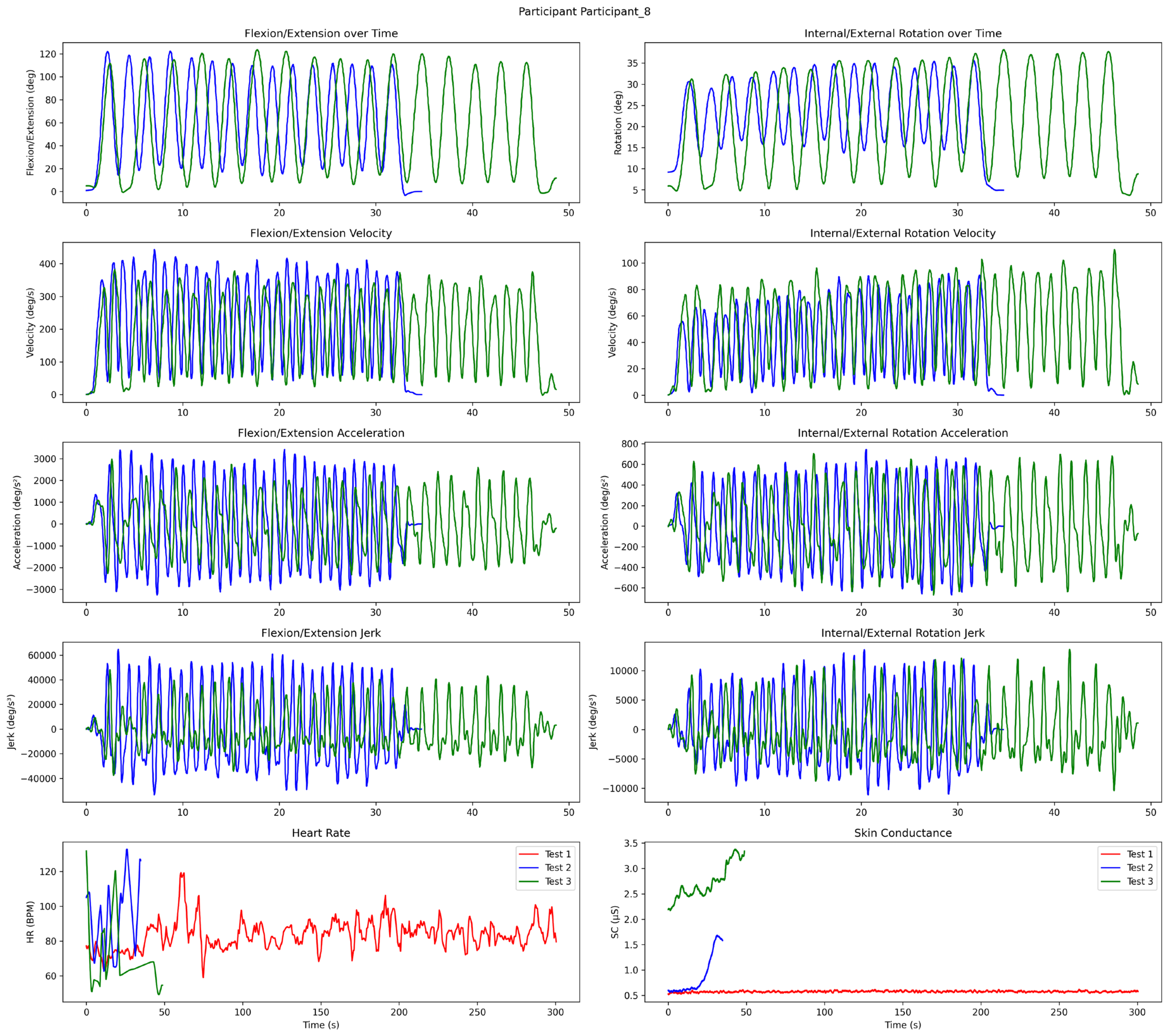
Participant: Participant_6

Metric	Test 1	Test 2	Test 3
Time (s)	300.61	47.14	70.08
Max Flexion/Extention (deg)	103.44	111.85	106.36
Min Flexion/Extention (deg)	103.14	-1.83	-4.52
Max Internal/External Rotation (deg)	-3.92	12.54	15.36
Min Internal/External Rotation (deg)	-4.68	-2.38	-3.58
Avg HR (BPM)	73.04	83.25	89.61
Max HR (BPM)	89.14	119.77	119.48
Min HR (BPM)	62.18	51.27	53.85
Avg SC (μS)	3.27	3.76	5.67
Max SC (μS)	3.45	4.38	6.39
Min SC (μS)	3.12	3.25	4.92
Avg Velocity Flexion (deg/s)	0.01	180.30	150.28
Max Velocity Flexion (deg/s)	0.10	351.26	344.75
Avg Acceleration Flexion (deg/s²)	-0.00	3.53	-1.53
Max Acceleration Flexion (deg/s²)	0.42	2487.05	2625.11
Avg Jerk Flexion (deg/s³)	-0.02	-324.45	-264.25
Max Jerk Flexion (deg/s³)	5.07	43815.53	42598.32
Avg Velocity Rotation (deg/s)	0.02	22.82	24.04
Max Velocity Rotation (deg/s)	0.49	44.89	52.97
Avg Acceleration Rotation (deg/s²)	0.00	1.06	0.28
Max Acceleration Rotation (deg/s²)	3.59	331.76	326.55
Avg Jerk Rotation (deg/s³)	-0.03	-56.87	-41.76
Max Jerk Rotation (deg/s³)	49.98	6356.30	5224.88
HRV RMSDD (ms)	0.15	0.61	0.57
HRV SDNN (ms)	49.02	212.40	167.01



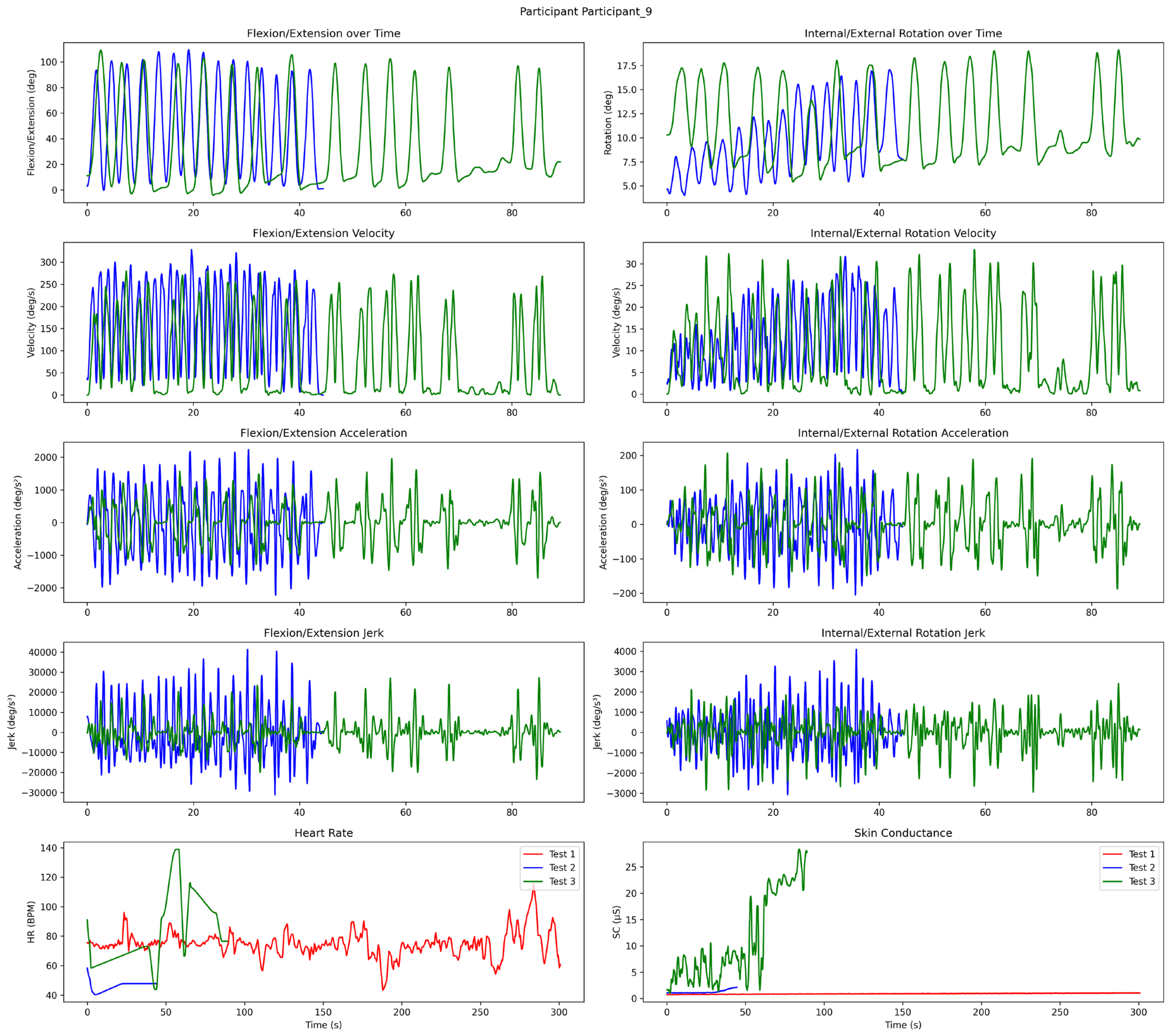
Participant: Participant_7

Metric	Test 1	Test 2	Test 3
Time (s)	300.42	27.63	57.02
Max Flexion/Extention (deg)	-0.05	105.76	119.14
Min Flexion/Extention (deg)	-0.07	-8.23	-12.42
Max Internal/External Rotation (deg)	-0.87	21.19	19.72
Min Internal/External Rotation (deg)	-0.94	5.81	-1.91
Avg HR (BPM)	64.54	72.79	70.10
Max HR (BPM)	116.18	144.86	101.63
Min HR (BPM)	43.61	43.98	48.54
Avg SC (μS)	1.22	2.58	8.79
Max SC (μS)	1.68	4.45	13.59
Min SC (μS)	0.92	1.59	4.58
Avg Velocity Flexion (deg/s)	0.00	198.24	168.19
Max Velocity Flexion (deg/s)	0.03	372.97	382.98
Avg Acceleration Flexion (deg/s²)	-0.00	10.98	1.60
Max Acceleration Flexion (deg/s²)	0.20	3004.48	2849.76
Avg Jerk Flexion (deg/s³)	-0.00	-84.26	-298.95
Max Jerk Flexion (deg/s³)	5.99	63442.45	52532.90
Avg Velocity Rotation (deg/s)	0.01	20.29	17.62
Max Velocity Rotation (deg/s)	0.05	42.37	58.88
Avg Acceleration Rotation (deg/s²)	0.00	0.94	-1.23
Max Acceleration Rotation (deg/s²)	0.35	342.32	502.20
Avg Jerk Rotation (deg/s³)	-0.01	-13.70	-36.49
Max Jerk Rotation (deg/s³)	5.30	6235.25	7972.64
HRV RMSSD (ms)	0.38	0.49	0.50
HRV SDNN (ms)	191.61	280.22	161.15



Participant: Participant_8

Metric	Test 1	Test 2	Test 3
Time (s)	300.42	34.72	48.68
Max Flexion/Extention (deg)	108.39	122.35	123.55
Min Flexion/Extention (deg)	73.58	-3.29	-1.41
Max Internal/External Rotation (deg)	28.74	35.60	38.15
Min Internal/External Rotation (deg)	21.91	4.86	3.70
Avg HR (BPM)	83.63	92.72	69.64
Max HR (BPM)	119.28	132.74	131.72
Min HR (BPM)	59.02	62.66	49.19
Avg SC (µS)	0.57	0.88	2.72
Max SC (µS)	0.62	1.68	3.38
Min SC (µS)	0.51	0.56	2.17
Avg Velocity Flexion (deg/s)	0.35	225.35	196.39
Max Velocity Flexion (deg/s)	83.86	442.94	381.87
Avg Acceleration Flexion (deg/s²)	-0.03	4.60	6.34
Max Acceleration Flexion (deg/s²)	435.89	3415.48	2971.81
Avg Jerk Flexion (deg/s³)	-0.44	-211.28	-189.61
Max Jerk Flexion (deg/s³)	4858.89	64659.47	48085.00
Avg Velocity Rotation (deg/s)	0.16	44.37	51.67
Max Velocity Rotation (deg/s)	11.67	92.06	110.14
Avg Acceleration Rotation (deg/s²)	0.00	0.87	2.22
Max Acceleration Rotation (deg/s²)	64.50	744.26	704.26
Avg Jerk Rotation (deg/s³)	-0.07	-42.76	-48.22
Max Jerk Rotation (deg/s³)	1271.48	13548.94	13625.30
HRV RMSDD (ms)	0.32	0.60	0.49
HRV SDNN (ms)	73.92	153.63	146.60



Participant: Participant_9

Metric	Test 1	Test 2	Test 3
Time (s)	300.77	44.42	89.11
Max Flexion/Extention (deg)	97.49	109.43	109.16
Min Flexion/Extention (deg)	94.71	-0.25	-4.16
Max Internal/External Rotation (deg)	9.00	17.06	19.13
Min Internal/External Rotation (deg)	8.61	4.03	5.41
Avg HR (BPM)	74.81	46.15	83.03
Max HR (BPM)	115.61	58.30	139.01
Min HR (BPM)	43.27	40.28	43.73
Avg SC (μS)	0.89	1.25	11.20
Max SC (μS)	1.06	2.12	28.36
Min SC (μS)	0.71	1.02	1.02
Avg Velocity Flexion (deg/s)	0.05	164.56	84.97
Max Velocity Flexion (deg/s)	2.31	328.16	280.94
Avg Acceleration Flexion (deg/s²)	-0.00	-16.92	0.64
Max Acceleration Flexion (deg/s²)	9.70	2237.30	1957.60
Avg Jerk Flexion (deg/s³)	-0.11	-159.63	-101.29
Max Jerk Flexion (deg/s³)	78.05	41398.07	27316.70
Avg Velocity Rotation (deg/s)	0.01	12.83	9.37
Max Velocity Rotation (deg/s)	0.20	31.68	33.25
Avg Acceleration Rotation (deg/s²)	0.00	-1.15	0.15
Max Acceleration Rotation (deg/s²)	1.29	217.31	206.99
Avg Jerk Rotation (deg/s³)	-0.03	-9.59	-11.14
Max Jerk Rotation (deg/s³)	13.05	4096.49	2412.76
HRV RMSDD (ms)	0.34	0.17	0.35
HRV SDNN (ms)	104.28	84.94	206.46

Appendix Z: Questionaire anwsers

What is your paticipant number?

9 antwoorden

4

6

1

3

7

8

9

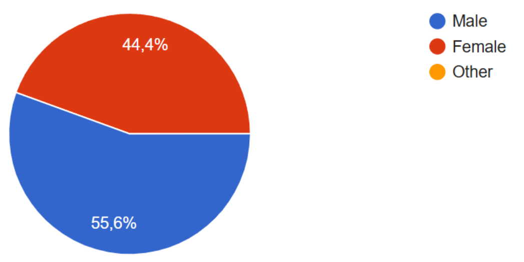
2

5

What is your gender?

Diagram kopiëren

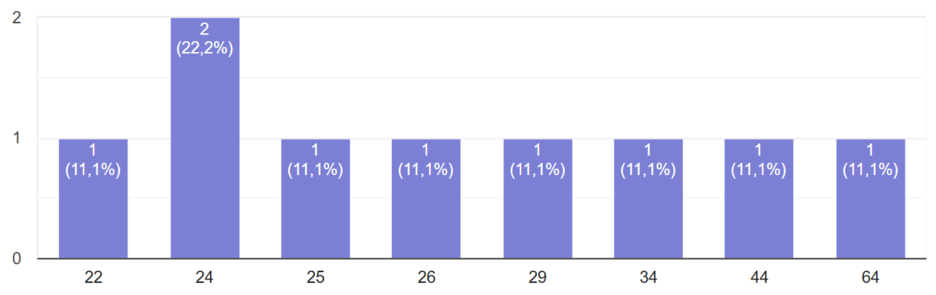
9 antwoorden



What is your age?

Diagram kopiëren

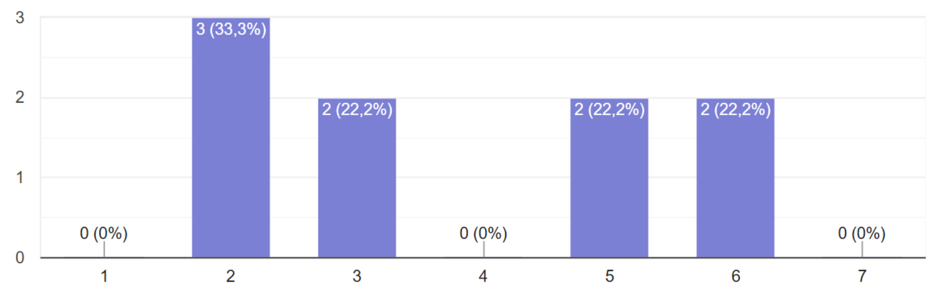
9 antwoorden



What is your fitness level?

Diagram kopiëren

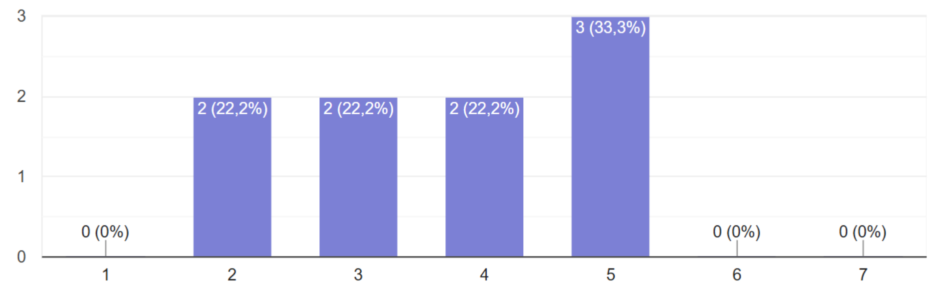
9 antwoorden



How fast are you usually experiencing stress?

Diagram kopiëren

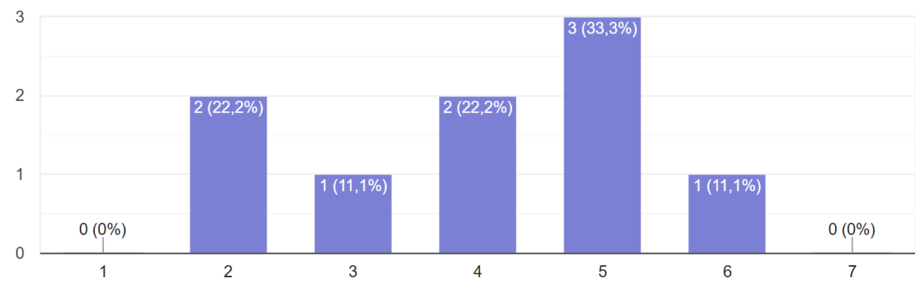
9 antwoorden



How hard do you find counting backwards in general?

Diagram kopiëren

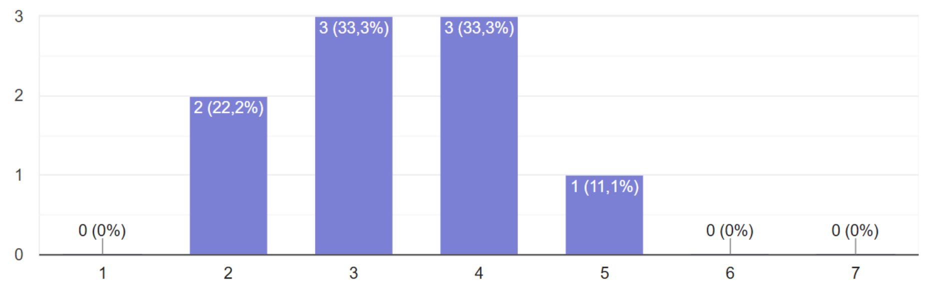
9 antwoorden



What level of exercise do you label the squats (physical activity)?

Diagram kopiëren

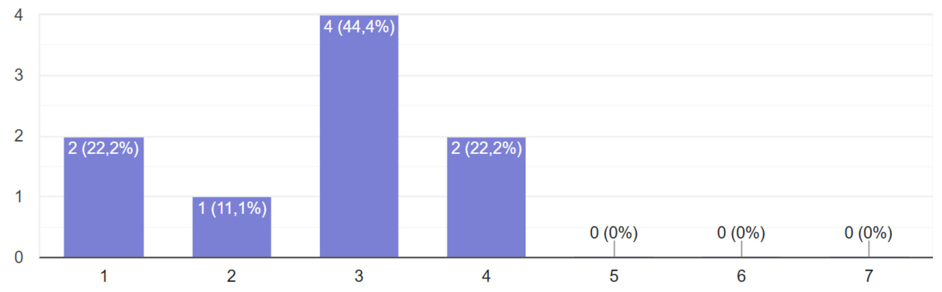
9 antwoorden



What emotional intensity did you experience during the only squats exercise?

Diagram kopiëren

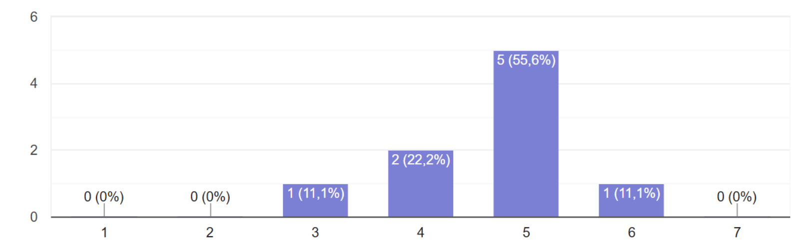
9 antwoorden



What emotional intensity did you experience with the exercise with the extra task (counting backwards)?

Diagram kopiëren

9 antwoorden



Can you descripe what kind of emotion you had during the exercise with extra task (counting backwards) and how was this different from exercising without the extra task?

9 antwoorden

I felt quite stressed. I tried to keep the movement going while counting, but multitasking is not exactly my strength, and maintaining my balance became more challenging.

I didn't feel much of a difference, but staying consistent was definitely more difficult. I was curious to figure out how to perform both tasks at the same time, and I found it quite challenging.

without extra task i was only focussing on doing the squats. with the extra exercise I felt a little stress because I had to concentrate on doing the squats as well as counting backwards, which I wanted to to without errors. I think the stress was to find a balance between the 2 tasks, I think I eventually found a balance by focussing on the counting and doing the squats more on autopilot.

It was quite stressful. I felt as though I were constantly in a rush. There was a certain pressure to perform, which left me feeling frustrated when I couldn't think of the correct number. During the first exercise I felt more confident and in control.

Stress, doubt if I got the number sequence right

The extra task of focussing on the counting made me fully focus on that. Which was interesting, because I experienced a lot less physical strain (mentally that is) than I did during the first set. The actual strain was about the same probably, but the counting greatly affected my interpretation

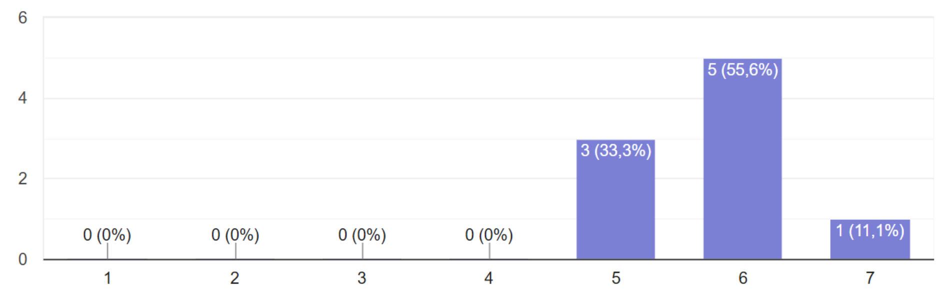
2 taken zijn steeds moeilijker te combineren, in begin denk je aan de squats, daarna meer aan het terugtellen.

I felt a bit stressed out in the last test because i could not really keep a good rhythm in my movement. Also a bit of frustration because i could not get my movement as great in the last test.

It was more challenging than I expected, and I found myself feeling a bit unfocused. As time went on, the frustration started to build.

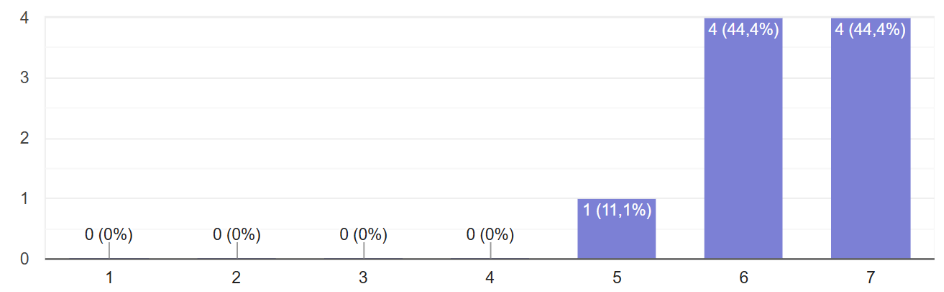
How much did the extra task (counting backwards) effect your movement? Diagram kopiëren

9 antwoorden



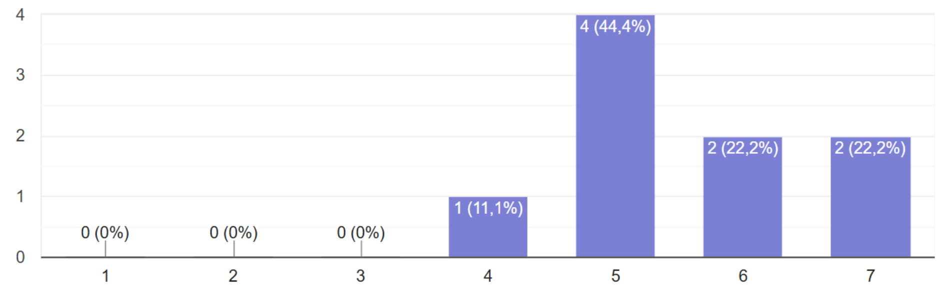
How intutive was it to place the wearable system using the instructions? Diagram kopiëren

9 antwoorden



How comfortable was it to wear the wearable system? Diagram kopiëren

9 antwoorden



After seeing your knee load and body stress data in the overview above, how would you describe your current state? and what would you do?

9 antwoorden

To be honest, I am not sure how to interpret this. Am I supposed to be filling these rings? As I understand it, the knee strain reflects how much I've moved, recovery shows how much I've engaged with my treatment plan today, and emotional load represents the level of stress I've experienced throughout the day. Based on that, it seems I should focus more on supporting my recovery process and finding ways to reduce stress.

I do not know the word 'strain' but it shows up in red so maybe my knee is not in a good condition and I have not recovered enough. I was a bit stressed today so maybe taking some time to adress this.

I don't know what knee strain is, so the 58% doesn't say anything to me to be honest. But because it is red I think my current state is not that well. I would interpret red as bad, orange (the recovery) as medium and green as good. But I only see red, orange and grey. Then I thought maybe grey are just facts without any good/bad judgement, but I also don't think that's the case with emotional load. So I'm confused by the colours. Also I'm not sure what the knee strain, recovery and emotional load exactly mean. Because the shapes are circles that are not fully loaded, I could interpret that also as a circle that you have the fill during the day. But then again, Ii think knee strain is confusing because the circle of knee strain is red, but more filled that the orange recovery circle.

I believe I may have placed too much strain on my knee because of the red circle, although I'm also carrying a heavier emotional load, which leaves me feeling a bit confused. I think it's important for me to focus on fully filling my recovery circle, bringing it to 100%. Taking more rest the following day might what i need to do

My current state would be being close to my comfortable limit, especially emotionally wise. I would take it easy on myself on this day, maybe incorporating a rest day and letting myself get back up to recovery. My knee feels okay probably so maybe some light stretching would be good, but not a heavy workout.

I think I did pretty bad, based off the colour of knee strain.

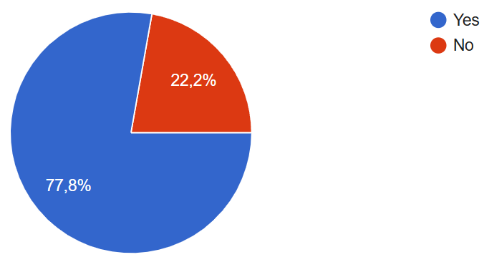
focus on my emotional stress so i can improve my recovery, my knee strain is relative good so i can do more if i relax more.

I would be a bit concerned because the recovery is low while my knee strain is relativly high, also I look quit stressed in this overview. I would find more time to recover and relax more the next the day.

Not that good. I think I need to manage my stress levels better throughout the day and make more time to relieve my emotional load. Taking a moment to relax or fitting in a short nap might really help.

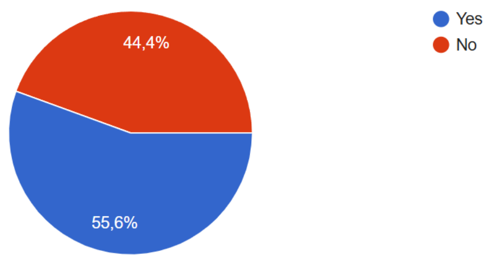
Knee strain reflects the amount of movement throughout the day, recovery indicates the percentage of time the body is in a resting state, and emotional load represents the level of stress, anxiety, and pain responses experienced by the body. With this explanation, would you now understand how to interpret the overview? Diagram kopiëren

9 antwoorden



HRV (heart rate variability) reflects how your body is recovering and responding to stress. Higher HRV usually means better recovery or readiness. I use this to estimate how prepared your body is for physical activity. Did you know about HRV before? Diagram kopiëren

9 antwoorden



Given the definitions of each metric—knee strain as daily movement, recovery as the percentage of time the body is at rest, and emotional load as the body's stress, anxiety, and pain responses—how would you interpret the overall data?

9 antwoorden

I would try to relax more the next day trying to get emotional load down and get my body more in the resting state.

similar as above, I do not get it. do the rings change color from red to green or do I need to do something else with these.

I would interpret knee strain as a circle that I have to fill during the day. Now it is red so I have to do more exercises today to complete the circle. I don't know how to interpret the recovery, I don't know if I have to complete the circle or that it just has to be green/orange/red or something. Also, I don't know how to interpret the emotional load because I would expect a kind of judgement about the state: is it good or bad at this moment. But because of the high percentage (78%) I think I had a lot of stress.

Ah, I see so it's really about balancing the different metrics in the overview. I feel that I need to relax more and allow my body more time in the recovery state. I'm starting to wonder whether the circles are the most accurate way to represent this. Perhaps a different type of visualisation, something that better conveys balance might be more helpful. Also, I'm not entirely sure: is red necessarily a bad sign?

My interpretation of recovery would change a bit, since having 44% shows that I I only am in rest less than half of the time. This will make me give myself more rest, maybe going for a nice walk but not any heavy exercise at all.

That I did a decent job today, and that the recovery is at a low side. The fact that these values don't add up to 100 percent seems a bit weird though

knee strain can be more, less rest, i must be more relaxed.

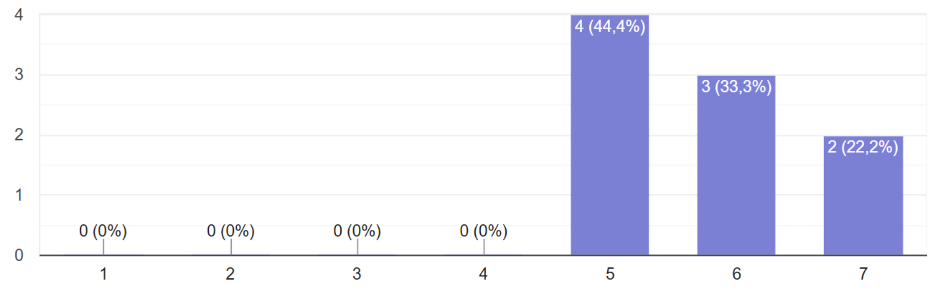
The same as above, I have experience with Woop that has a similar data overview.

I think I got it the first time, is similar as smartwatch

How clear was the description of HRV in the previous question?

Diagram kopiëren

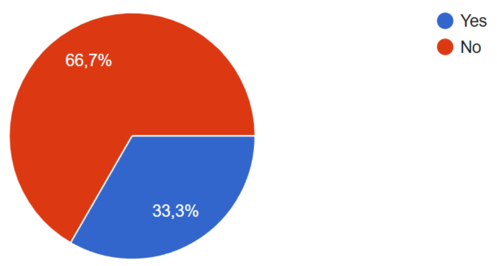
9 antwoorden



SC (Skin conductance) reflects changes in skin conductivity linked to emotional or physiological arousal (stress, pain or excitement). A sudden increase in SC can indicate strong emotional response. We use this to detect how emotions may influence your movement patterns. Did you know about this metric?

Diagram kopiëren

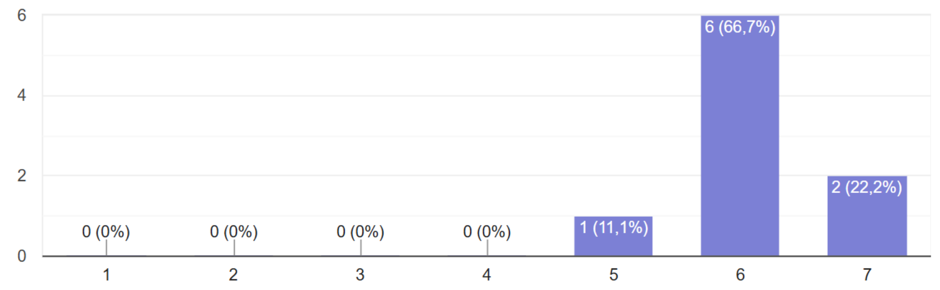
9 antwoorden



How clear was the description of SC in the previous question?

Diagram kopiëren

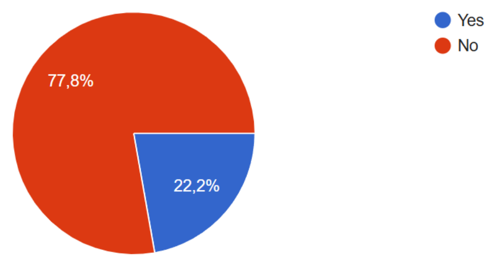
9 antwoorden



"Jerk" is used to describe the smoothness of movement. A higher Jerk can indicate motor control issues or stress. Did you know about this metric?

Diagram kopiëren

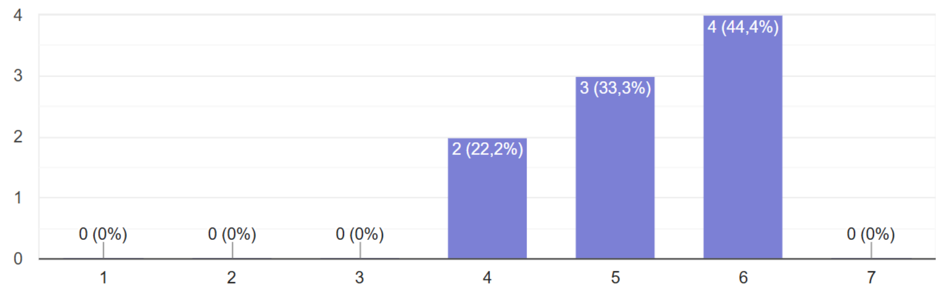
9 antwoorden



How clear was the description of "jerk" in the previous question?

Diagram kopiëren

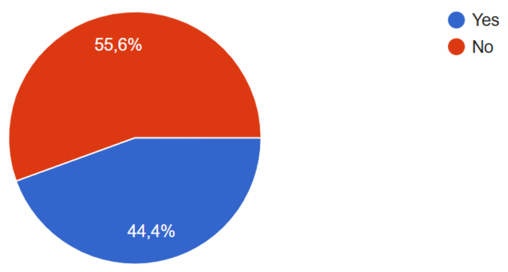
9 antwoorden



An important metric in knee rehabilitation is ROM, do you know what ROM means?

Diagram kopiëren

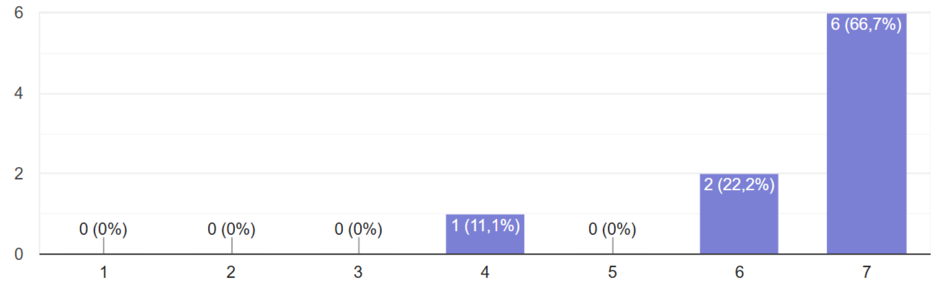
9 antwoorden



ROM stands for range of motion. In knee rehabilitation this stands for the angle of the knee. A common goal is to reach targets to increase ROM to a range of -5 to 130 ° . How clear was this description of ROM?

Diagram kopiëren

9 antwoorden



Is there anything else you'd like to share about your experience with the prototype or how the information was presented?

9 antwoorden

I really appreciated the modules on the leg, they were comfortable and felt effective. However, the wrist module wasn't quite as comfortable for me.

I would suggest adding some sort of explanation for what each metric in the overview actually means. Right now, it's pretty difficult to understand for me. But great test, I enjoyed the challenge.

I think the instruction page for sensor placement was very clear and intuitive. The only thing I was doubting about was if I had to place the sensors exactly on the right side of the body (as on the instrictions) or that I could also place it on my left side. And if it matters if all sensors are placed on the same side of the body or that I could place 1 sensor left and the other one on the right side

Intense experience. and cool concept!

The wristband was quite tight, so I would recommend something looser for daily useage.

Awesome job with the 3D printing!

it was a plesure

I really liked the comfort of the straps around my leg, however the strap around my wrist did not feel that comfortable. I think it is because of a prototype, but holding a case like this and the somewhat tight strap did not feel as comfortable as the rest of the system.

no

Appendix AA: Approved project brief

CHECK ON STUDY PROGRESS
To be filled in **by SSC E&SA** (Shared Service Centre, Education & Student Affairs), after approval of the project brief by the chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total		EC
Of which, taking conditional requirements into account, can be part of the exam programme		EC

★	YES	all 1st year master courses passed
	NO	missing 1st year courses

Comments:

Sign for approval (SSC E&SA)

Robin den Braber — Digitaal ondertekend door Robin den Braber Datum: 2024.11.25 08:53:30 +01'00'

Name: Robin den Braber   Date: 25-11-2024   Signature:

APPROVAL OF BOARD OF EXAMINERS IDE on SUPERVISORY TEAM -> to be checked and filled in by IDE's Board of Examiners

Does the composition of the Supervisory Team comply with regulations?

YES	★	Supervisory Team approved
NO		Supervisory Team not approved

Comments:

Based on study progress, students is ...

★	**ALLOWED** to start the graduation project
	NOT allowed to start the graduation project

Comments:

Sign for approval (BoEx)

Monique von Morgen — Digitally signed by Monique von Morgen Date: 2024.11.26 10:05:13 +01'00'

Name: Monique von Morgen   Date: 26/11/2024   Signature:

DESIGN FOR our future   TU Delft

Personal Project Brief – IDE Master Graduation Project

Name student Tim Bouwmeester   **Student number**

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title A patient-focused wearable for an engaging and supported knee injury recovery

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

75% of physiotherapy practitioners do not do their home exercises properly. Therefore, I co-founded Exertise, a startup initiative to make home physiotherapy more fun and engaging. Currently we are developing a solution with an IMU (inertial measurement unit) sensor in combination with an app to make the home physiotherapy more engaging with the use of gamification and active feedback.

At Exertise our main stakeholder is the patient. Other stakeholders of Exertise are: medical experts like physiotherapist, surgeons and also insurance companies and businesses.

During our efforts, we encountered many patients with knee injuries or a history of knee injuries. A common theme among them was the struggle with fear of moving as freely as they did before the injury, along with a persistent sense of instability, even after completing rehabilitation. We found it challenging to apply our current solution effectively to this issue, which presents a valuable opportunity for me in this graduation project to explore a more tailored approach to address this specific problem of knee injuries.

→ *space available for images / figures on next page*

DESIGN FOR our future   TU Delft

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

Knee injuries, such as ACL (anterior cruciate ligament) tears, often leave patients feeling insecure about their knee's stability, even after intensive rehabilitation. This insecurity stems largely from a fear of re-injury, which can hinder recovery in much the same way that inconsistent home exercise routines do.
A solution that offers continuous guidance throughout rehabilitation and post-recovery could help patients regain confidence in their knee's performance, reduce the risk of re-injury, and boost engagement during exercises. For healthcare professionals, such as physiotherapists, this would also provide valuable insights into patients' activities outside of clinical sessions, allowing for quicker adjustments to treatment plans.
For Exertise, this product represents an opportunity to expand its offerings within the growing e-health market. Potential users include physiotherapists, athletes, and individuals undergoing or at risk of reinjury. Additionally, this solution could lower the cost of knee injury treatment by reducing in-person visits and enabling remote monitoring, thereby easing the burden on healthcare systems. Collecting this data could support better recovery outcomes and improve future rehabilitation programs.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence)
As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Designing a patient-centred wearable that enables knee rehabilitation progress tracking, improve engagement and enhances post-recovery support

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

This project will run parallel to Exertise's other developments and will be an independent project focused on knee rehabilitation for my personal graduation. I will follow the Double Diamond design framework, beginning with an exploratory research phase. A literature review will be conducted alongside interviews with experts such as physiotherapists and knee rehabilitation patients to gather data, understand the patient journey, and form a program of requirements and product scope.
Subsequently, an ideation phase will generate multiple potential solutions, which will be evaluated using predefined criteria such as feasibility, user acceptance, and therapeutic value. Selected concepts will undergo further validation through discussions with target users.
In the development phase, I aim to create a functional prototype of the chosen concept and test the prototype for technical accuracy of the data and user experience. Furthermore, I would like to assess the prototype's potential effectiveness in knee injury treatment.

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a ***kick-off meeting, mid-term evaluation meeting, green light meeting*** *and* ***graduation ceremony.*** *Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	4 Nov 2024?
Mid-term evaluation	10 Jan 2025
Green light meeting	7 Mar 2025
Graduation ceremony	8 Apr 2025

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	✓
For how many project weeks	20
Number of project days per week	5

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

I am motivated to pursue this project because I believe a tailored solution could generate more accurate data compared to Exertise's current solution that only measures movement data (ROM(range of motion) and speed). For example doing gait analysis, measuring forces or capturing muscle activity. Therefore help people with knee injuries better in understanding their own body while being more confident during their rehabilitation.
I am confident in succesfully completing this assigment with my skills in prototyping and testing and experiences gathered during the development of Exertise. Furthermore I learned valuable testing and validation skills during my internship with Spark.
In this project I want to learn more about incoperating biomechanics in product design. Furthermore I like to improve my scientific reasoning and documentation skills. I often struggle with documentation of the designproces because I am to focused on building and testing without thoroughly recording results, which poses challenges later on in communcation or writing a report.

2024-2025