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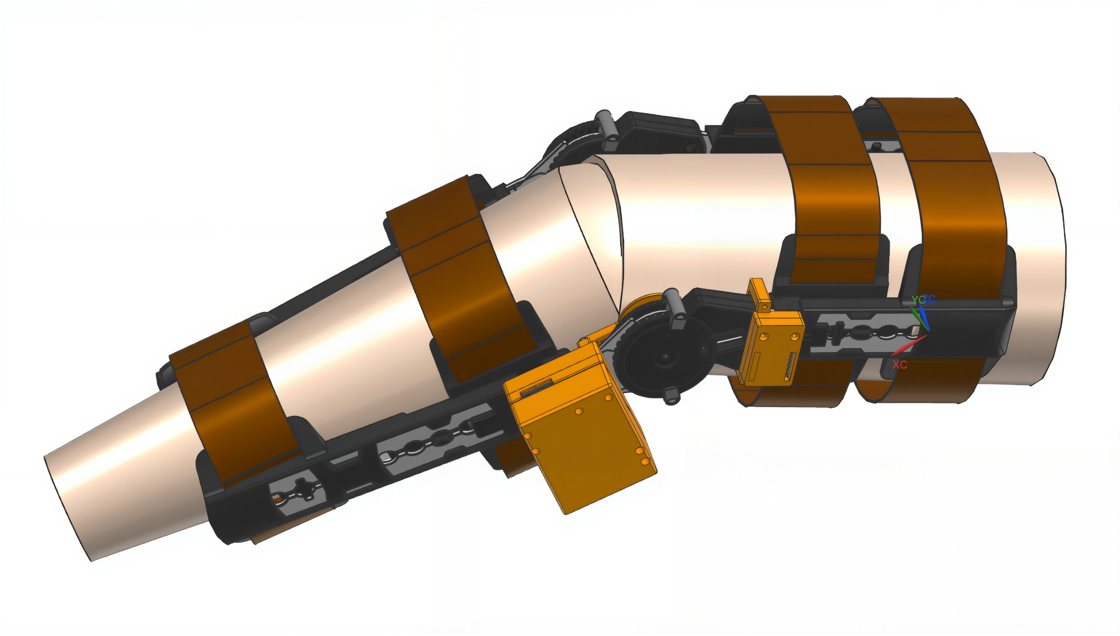

# Design and Development of a Novel Sensorized Orthosis for Orthopedic Rehabilitation

## Towards Objective Biomechanical Assessment and Intelligent Rehabilitation

Master's thesis in Systems, Control and Mechatronics

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2025
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Master's thesis 2025

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Cover: Concept picture of the Proposed Sensorized Orthosis for Orthopedic Rehabilitation.

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# Abstract

This thesis presents the design, development, and implementation of a novel sensorized orthosis for orthopedic rehabilitation. The system addresses the lack of quantitative feedback in traditional passive braces by integrating compact sensing and data communication modules into a lightweight and modular structure. An absolute rotary encoder and two six-axis IMUs were employed to measure knee joint angle and motion dynamics in real time. The embedded controller, based on an ESP32-S3 microcontroller, supports high-frequency data acquisition, local microSD logging, and wireless communication with the ROS 2 framework, enabling both offline analysis and interactive applications.

The system was designed as a fully independent and non-invasive add-on to a commercial postoperative brace, maintaining clinical compatibility while adding sensing capability. The complete system weighs approximately 180 grams and allows rapid attachment and removal without altering the brace's mechanical properties. Experimental validation confirmed stable and synchronized sensor performance, accurate joint-angle estimation, and reliable differentiation between correct and incorrect rehabilitation motions.

The integration of the existing Unity3D-based rehabilitation game with the proposed system successfully validated its feasibility and immense potential in intelligent, interactive rehabilitation. This system bridges the technological gap between conventional orthopedic braces and intelligent robotic rehabilitation devices, establishing a solid foundation for achieving intelligent, quantitative, and personalized rehabilitation assessment and training.

**Keywords:** sensorized orthosis, knee rehabilitation, motion sensing, IMU, rotary encoder, ESP32, ROS2, game-based rehabilitation, wearable system.

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Yuhong Zhou, Gothenburg, October 2025

# List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

| | |
|---|---|
| CAD | Computer-Aided Design |
| EMG | Electromyography |
| IMU | Inertial Measurement Unit |
| SPI | Serial Peripheral Interface |
| PLA | Polylactic Acid |
| PA-CF | Polyamide Carbon Fiber Reinforced |
| PC | Polycarbonate |
| ROM | Range of Motion |
| Li-Po | Lithium-Polymer |
| I2C | Inter-Integrated Circuit |
| UART | Universal Asynchronous Receiver-Transmitter |
| SDIO | Secure Digital Input Output |
| ROS2 | Robot Operating System 2 |

# Contents

# List of Figures

# 1

# Introduction

## 1.1 Background and Motivation

Orthopedic tendon injuries, particularly those involving the knee joint, are highly prevalent across various age groups and can result from acute trauma, degenerative changes, or cumulative mechanical overload. In older adults, such injuries are predominantly associated with age-related degeneration or accidental falls, while in younger and athletic populations, they are often attributed to sports-related overuse, excessive loading, or improper training [1]-[4]. Among these, quadriceps and patellar tendon injuries are the most common, significantly affecting mobility, stability, and daily function of the lower limb [5], [6].

Rehabilitation following tendon reconstruction or repair represents a critical yet delicate stage in recovery. It requires precise motion control, appropriate load management, and progressive strengthening to restore tendon elasticity and joint function [7]. However, current rehabilitation practices remain largely manual and subjective, relying on therapist supervision and patient feedback. This limits the consistency, objectivity, and long-term traceability of recovery progress. Conventional follow-up methods, which require frequent in-person visits, are time-consuming and costly. More critically, the lack of quantitative data collection hinders clinicians from making personalized, evidence-based decisions in adjusting rehabilitation parameters [8], [9].

These challenges have led to growing research interest in sensorized orthoses and smart braces. By integrating sensors such as IMUs and rotary encoders, these wearable devices are capable of measuring joint angles, monitoring movement patterns, and capturing load distributions [10]-[12]. Such systems aim to enable data-driven rehabilitation and objective feedback while maintaining user safety and comfort.

## 1.2 State of the Art

### 1.2.1 Conventional Orthoses for Knee Rehabilitation

Conventional postoperative knee orthoses, or knee braces, are commonly used in clinical practice to support recovery after ligament or tendon reconstruction. These devices typically feature bilateral mechanical frames with adjustable hinges that restrict knee flexion and extension according to the rehabilitation phase [13]. They effectively stabilize the joint, protect the surgical repair, and prevent excessive motion that could jeopardize healing.

However, conventional braces rely solely on mechanical structures and lack embedded sensing or data acquisition capabilities. Without objective feedback, clinicians must depend on visual inspection and patient self-reporting to assess recovery, making it difficult to track progress, adjust rehabilitation movements and parameters, or ensure appropriate loading. These limitations constrain the potential for personalized and data-driven rehabilitation and may increase the risk of delayed recovery or secondary injury.

These challenges have driven the development of sensor-integrated orthoses and exoskeleton systems that combine the inherent safety of passive braces with the intelligent, data-driven capabilities of modern rehabilitation technologies.

### 1.2.2 Robotic and Smart Devices for Rehabilitation

Over the past two decades, rehabilitation robotics has rapidly advanced, leading to the development of various exoskeleton systems such as HAL, ReWalk, Indego, and Ekso. These actively actuated devices are designed to assist motor training and gait recovery, particularly for patients with neurological disorders such as stroke or spinal cord injury. Through multi-sensor feedback and adaptive control algorithms, they enable precise movement tracking and have demonstrated significant therapeutic benefits [14].

However, most existing exoskeletons are not optimized for orthopedic rehabilitation. They are typically heavy, costly, and mechanically complex, making them unsuitable for postoperative tendon recovery, where safety and controlled motion restriction are critical. Furthermore, their rigid structures often fail to accommodate the six degrees of freedom of the human knee, potentially causing misalignment and unwanted joint forces [13]. In addition, most current designs rely on a single-sided frame, which provides limited medial-lateral protection and insufficient joint stabilization for postoperative orthopedic rehabilitation.

Consequently, an increasing amount of research has focused on sensorized passive and quasi-passive exoskeletons. These systems are lightweight, modular, and inherently safe, and can provide joint stabilization and controlled motion restriction without active actuation [11], [15], [16]. By integrating embedded sensors and intelligent feedback, such devices aim to deliver data-driven monitoring and fundamental physical assistance to better support the rehabilitation process.

Despite these advancements, current smart orthoses still lack an integrated framework that unifies sensing, safety, and feedback. This gap limits their ability to meet real postoperative rehabilitation needs. To address this issue, the present study proposes a sensorized orthopedic orthosis that combines high-resolution motion sensing with adjustable range control to provide quantitative and reliable feedback during rehabilitation.

Notably, robotic systems in neurorehabilitation have accumulated transferable experience in sensing, feedback, and control strategies. Introducing these principles into orthopedic rehabilitation can establish a "neuro-to-orthopedic" transfer learning approach, paving the way for safer and data-driven recovery systems. Furthermore, the gamification training paradigm widely adopted in neurorehabilitation can also be transferred to orthopedic contexts to enhance patient engagement and motivation, fostering personalized, interactive, and intelligent rehabilitation.

## 1.3 Clinical Motivation and Design Rationale

### 1.3.1 Clinical Motivation

Early postoperative rehabilitation following tendon or ligament surgery requires precise motion control and a gradual reintroduction of mechanical load to ensure safe and effective recovery. During this period, active robotic exoskeletons—although highly effective in neuro rehabilitation—are often too complex, expensive, and potentially unsafe for use in tendon rehabilitation. In contrast, passive exoskeletons offer a lightweight, low-cost, and inherently safe alternative suitable for both clinical and home-based settings, particularly when joint protection and controlled motion take precedence over active assistance.

However, the greatest limitation of existing passive exoskeleton systems and sensorized devices lies in the lack of integrated sensing and data feedback. Without quantitative motion monitoring, clinicians are unable to accurately evaluate patient progress or adjust rehabilitation protocols in a timely and personalized manner, leading to inconsistent treatment outcomes. This gap highlights the need for a sensing-enabled passive rehabilitation system that combines the mechanical safety of traditional braces with the data-driven insight of modern wearable technology [8], [15].

To address these challenges, this study aims to design, develop, and experimentally validate a novel sensorized orthosis specifically intended for postoperative knee rehabilitation. Building on the mechanical principles of conventional orthopedic braces, the proposed system integrates mechanical protection, sensor-based motion monitoring, and wireless data acquisition into a compact, lightweight, and ergonomically optimized structure. In addition, the orthosis is suitable for both clinical rehabilitation and interactive training scenarios, enhancing patient engagement and enabling continuous, end-to-end monitoring of rehabilitation progress.

### 1.3.2 Design Rationale

Rather than developing a completely new exoskeleton frame, this study adopts an existing, clinically validated orthopedic brace as the structural foundation. This approach provides several key advantages. First, clinically approved braces have already demonstrated safety, comfort, and biomechanical effectiveness in postoperative use, promoting better acceptance among both therapists and patients [17]-[19]. Second, modifying a certified device minimizes regulatory barriers and facilitates translation into clinical practice, as incremental innovations are easier to approve compared to entirely new robotic systems [20]. Finally, this strategy ensures immediate compatibility with standard rehabilitation workflows, enabling seamless integration of sensing modules without altering familiar brace geometries or usage protocols.

## 1.4 Research Objectives and Scope

**Research Objectives:**

1. **System design and prototyping** – Design and construct a lightweight, detachable sensorized orthosis that preserves the mechanical functionality of conventional knee orthoses while introducing modularity for sensor integration and system scalability.

2. **Sensor integration and data acquisition of sensors** - Implement a multi-sensor setup combining IMUs and an encoder for real-time measurement of knee motion angles, angular velocity, and load patterns. The system supports both local data logging and wireless communication to enable secure and remote monitoring.

3. **Interactive rehabilitation and data validation** – To demonstrate the application feasibility of the sensorized orthosis in intelligent, interactive rehabilitation through a transfer-based, gamified rehabilitation experiment. Concurrently, to comprehensively evaluate its motion tracking accuracy, system responsiveness, wearing comfort, and operational stability under practical usage scenarios.

4. **System evaluation and improvement** – To analyze the collected experimental data to assess system performance, identify limitations, and propose directions for future improvements toward a fully adaptive, data-driven intelligent rehabilitation platform.

**Research Scope:**

This study covers the mechanical design, sensor fusion and data acquisition, and experimental validation of the sensorized orthosis prototype. The research focuses on establishing a functional proof-of-concept that demonstrates safe operation, reliable sensing, and effective human–device interaction. Large-scale clinical trials and advanced intelligent algorithms for automatic assessment and intelligent rehabilitation are beyond the scope of the current study, but are identified as future extensions of this work.

## 1.5 Structure of the Thesis

This thesis is organized into six chapters, each addressing a specific stage of the research and development process of the proposed passive knee exoskeleton system.

- **Chapter 1 – Introduction**

  Introduces the clinical motivation, background, and research context of post-operative tendon rehabilitation. Review the current state of orthopedic orthosis and exoskeleton research, identifies existing limitations, and defines the objectives, scope, and contributions of the proposed work.

- **Chapter 2 – Theory**

  This chapter outlines the theoretical foundation of the proposed sensorized orthosis. It summarizes key principles of postoperative tendon rehabilitation, reviews existing orthopedic orthoses and exoskeletons, and defines the clinical and design requirements guiding system development.

- **Chapter 3 – Methods**

  This chapter describes the design and implementation of the proposed sensorized orthosis, including components selection, mechanical structure, and electronic system architecture. It outlines how sensing, data logging, and wireless communication were integrated to enable accurate motion monitoring and safe postoperative rehabilitation.

- **Chapter 4 – Results and Discussion**

  Present and analyze the experimental results, including prototype implementation, data accuracy, and motion pattern recognition. The findings are discussed in relation to the research objectives, highlighting both the feasibility of the system and its existing limitations.

- **Chapter 5 – Conclusion and Future Work**

  Summarizes the main achievements of the study and discusses potential improvements. Future research directions include advanced data analysis, adaptive feedback control, and clinical deployment for long-term rehabilitation monitoring.

In summary, this section outlines the overall structure of the thesis. Each chapter is organized to reflect a logical progression from clinical motivation and theoretical background to system design, experimental validation, and future development. Together, these chapters present a comprehensive overview of the research and development process behind the proposed sensorized orthosis.

# 2

# Theory

## 2.1 Orthopedic Rehabilitation Protocols

The postoperative rehabilitation process for knee tendon injuries is structured into three progressive stages, each corresponding to a distinct biological phase of tendon healing and functional restoration. This phase-based rehabilitation strategy aligns with clinical guidelines, emphasizing the gradual introduction of mechanical load to facilitate neuromuscular re-education and the progressive restoration of functional activities, thereby ensuring a safe and effective recovery process [7], [21].

### 2.1.1 Phase I – Recovery (0 – 8 weeks)

The Recovery phase focuses on protecting the repaired tendon, managing postoperative pain and swelling, and initiating controlled muscle activation [7]. During this period, patients typically wear knee orthoses to maintain joint stability and protect the surgical site. Rehabilitation exercises are limited to gentle range-of-motion (ROM) and isometric contractions, such as quadriceps position, straight-leg raises, and ankle pumps, which help maintain joint flexibility, promote circulation, and prevent muscle atrophy.

At this stage, the primary role of knee orthoses is to provide mechanical protection and controlled motion. The adjustable ROM limiter allows clinicians to restrict knee flexion and extension to a safe range, while the dual-sided structure ensures stability and alignment of the limb. Together, these features protect the surgical repair while permitting controlled micro-movements necessary for early functional recovery.

### 2.1.2 Phase II – Transition (8 – 10/12 weeks)

The Transition Phase, also referred to as the "Acclimation to Load" stage, aims to progressively increase weight-bearing capacity, joint mobility, and muscular endurance [7]. As tendon integrity improves, patients transition from partial to full weight-bearing activities under supervision. Controlled closed-chain exercises (e.g., squats, step-ups, mini-lunges) and low-resistance strengthening routines are introduced to restore muscle balance, particularly in the quadriceps and hamstrings, which often exhibit postoperative inhibition [22].

During this stage, knee orthoses play an essential role in maintaining joint stability and protecting the healing tendon during progressive loading. By providing controlled motion restriction and medial–lateral stabilization, they enable patients to perform strengthening exercises safely while minimizing the risk of re-injury.

### 2.1.3 Phase III – Rebuild and Restore (10/12 weeks – 9 months)

The Rebuild and Restore phase focuses on restoring full strength, power, and agility, preparing patients for the return to everyday activity or athletic performance [7]. Once adequate ROM and muscle strength are achieved, rehabilitation advances to dynamic functional training, including jogging, directional changes, cutting, and jumping. Plyometric and agility drills help restore explosive power, movement coordination, and neuromuscular precision [23]. At this stage, the emphasis shifts to injury prevention, gait normalization, and movement efficiency. Functional assessments, such as balance testing and gait analysis, guide the progression to more demanding tasks.

In the advanced rehabilitation phase, knee orthoses are used primarily to improve joint stability during high-intensity movements. By providing external mechanical support, they help patients safely regain full functional mobility and confidence when returning to physical activity or sports.

## 2.2 Existing Orthoses in Orthopedic Rehabilitation

Orthopedic rehabilitation relies heavily on assistive devices that provide structural support, restrict excessive joint motion, and facilitate controlled functional recovery after surgery. Among these, knee orthoses and exoskeleton systems represent two major categories of external assistive technologies designed to enhance the safety and effectiveness of rehabilitation. Conventional knee braces primarily serve as mechanical protectors, ensuring joint stability and preventing re-injury during tendon or ligament healing, whereas robotic exoskeletons introduce active or semi-active control mechanisms to restore motor function and support intensive gait training. This section reviews the evolution of both approaches, highlighting their respective clinical roles, technological limitations, and the growing need for integrating sensing and data-driven feedback into future orthopedic rehabilitation systems.

### 2.2.1 Conventional Orthoses for Knee Rehabilitation

Conventional postoperative knee orthoses, also referred to as knee braces, are widely used in clinical settings to support recovery following ligament or tendon reconstruction. These devices typically consist of bilateral mechanical frames equipped with adjustable hinge joints that restrict knee flexion and extension according to the patient's rehabilitation phase [13]. As illustrated in Fig.2.1, these braces play a critical role in stabilizing the joint, protecting surgically repaired tissues, and preventing uncontrolled movements that may jeopardize the healing process. They are indispensable during the early phase of rehabilitation, where achieving an optimal balance between preserving joint mobility and ensuring structural protection is paramount.

**Figure 2.1:** Knee orthoses (brace) used at Sahlgrenska University Hospital, Gothenburg, Sweden: Enovis X-ROM Post-OP Knee Brace.

In addition to their use in the immediate postoperative period, knee braces also play a significant role in mid- and late-stage rehabilitation. As patients transition from partial to full weight-bearing, the brace provides progressive mechanical support, ensuring safe loading and maintaining proper joint alignment during gait retraining and strengthening exercises. Adjustable ROM limiters allow clinicians to gradually expand the permissible motion range, facilitating functional recovery while reducing the risk of re-injury. In later phases, knee orthoses are often used to enhance dynamic stability, providing patients with confidence during daily activities or sports reintegration.

Modern commercial braces, such as the Enovis X-ROM or DonJoy T-ROM models, feature lightweight aluminum alloy or carbon-fiber frames, soft ergonomic padding, and dial-based angle adjusters that allow clinicians to precisely set the permissible range of motion (ROM). This ensures both patient comfort and structural integrity while minimizing the risk of overstretching healing tendons or ligaments. Their straightforward mechanical configuration and adjustability make them cost-effective and easy to use in both hospital and home-based rehabilitation environments.

However, current knee orthoses generally lack integrated sensing or data acquisition capabilities, resulting in an absence of quantitative feedback to guide and evaluate the rehabilitation process. Without such objective and continuous measurements, clinicians and therapists must rely predominantly on visual observation and subjective patient feedback, which are inherently limited in accuracy and consistency. This prevents continuous monitoring of patient progress, making it difficult to detect subtle changes in joint performance, evaluate treatment efficacy, or adjust rehabilitation parameters in a timely manner.

Moreover, the absence of quantitative data restricts the implementation of evidence-based, adaptive rehabilitation strategies. Each patient's recovery trajectory can vary significantly depending on factors such as age, injury severity, surgical technique, and adherence to exercise routines. Without reliable sensing feedback, it becomes nearly impossible to develop personalized and dynamically adjustable rehabilitation protocols that respond to an individual's real-time physiological and biomechanical status. As a result, patients may be exposed to inappropriate loading conditions or insufficient mobilization, which can delay tendon healing, increase the risk of secondary injuries, and ultimately reduce the overall effectiveness and efficiency of the rehabilitation process.

These limitations have consequently generated a growing demand for advanced rehabilitation systems and exoskeleton devices equipped with comprehensive sensing, data logging, and feedback mechanisms. Such systems can provide real-time monitoring of joint kinematics and kinetics, enabling both clinicians and patients to access objective performance metrics during recovery.

### 2.2.2 Robotic and Smart Devices for Rehabilitation

During the past two decades, rehabilitation robotics has emerged as one of the most dynamic and transformative areas in assistive technology research. A wide range of exoskeleton systems such as HAL, ReWalk, Indego, and Ekso have been developed to facilitate motor training and gait recovery. These systems typically employ active actuation mechanisms that provide powered assistance to restore or enhance movement in patients with neurological impairments, including stroke, spinal cord injury, and cerebral palsy. Advanced control algorithms, combined with multi-sensor feedback (e.g. IMUs, EMG, encoders, and force sensors), enable precise motion tracking, torque regulation, and adaptive assistance, significantly improving rehabilitation outcomes and patient mobility [14].

However, despite their demonstrated success in neurorehabilitation, these active robotic systems are not optimized for orthopedic rehabilitation. They are typically heavy, expensive, and mechanically complex, often weighing over 20–30 kg and requiring external power supplies or support frames [14]. Such complexity introduces both operational challenges and safety concerns, especially during early-stage tendon or ligament recovery where controlled and limited motion is critical. Moreover, many of these systems adopt a unilateral support structure, which provides insufficient medial–lateral protection and fails to maintain proper joint stability—an essential requirement for postoperative knee rehabilitation. Excessive torque assistance or misalignment between the exoskeleton's mechanical axis and the anatomical knee axis can further cause abnormal joint loading, discomfort, or even secondary injury [13].

Moreover, most robotic exoskeletons are designed as standalone rehabilitation platforms, disconnected from the practical workflow of clinical orthoses. Their bulk and operational complexity limit their adoption outside specialized research centers. In addition, their high cost and maintenance requirements make them inaccessible for long-term home-based rehabilitation, which is crucial for sustained functional recovery.

To overcome these limitations, recent research has increasingly focused on passive and quasi-passive sensorized exoskeletons—lightweight, modular, and inherently safe systems that facilitate controlled motion without active actuation [11], [15], [16]. By integrating embedded sensing and intelligent feedback, these devices enable data-driven rehabilitation monitoring while maintaining mechanical simplicity and clinical safety.

However, current smart orthoses still lack a unified framework that effectively integrates sensing, safety, and feedback. Most designs provide only partial sensing functions—such as angle measurement or motion detection—without achieving system-level fusion or real-time clinical feedback. This limitation reduces their suitability for real postoperative rehabilitation, where safety, controlled motion, and quantitative monitoring are equally essential. To address this gap, a new generation of sensorized orthopedic orthoses is needed—combining the mechanical reliability of traditional braces with data-driven feedback and intelligent monitoring. Such an integrated approach can enable safer, more controllable, and personalized rehabilitation.

Robotic systems developed for neurorehabilitation have accumulated substantial knowledge in sensing, feedback, and adaptive control strategies, which can be effectively translated to orthopedic rehabilitation. Leveraging these principles forms a "neuro-to-orthopedic transfer learning" framework, enabling safer, data-driven, and patient-specific recovery systems. Moreover, the gamified training paradigms widely implemented in neurorehabilitation can also be adapted to orthopedic contexts to enhance patient engagement, motivation, and long-term adherence. Together, these transferable insights provide a theoretical foundation for developing interactive and intelligent orthopedic rehabilitation systems that bridge the gap between traditional braces and robotic technologies.

## 2.3 Clinical and Design Requirements

Building on the rehabilitation protocols outlined in the previous section, a comprehensive set of clinical and engineering requirements was defined to guide the design of the proposed sensorized orthosis. These requirements were developed through close collaboration with physiotherapists and occupational therapists at Sahlgrenska University Hospital, ensuring that the system meets both clinical relevance and technical feasibility. The formulation process involved multiple rounds of consultation, during which feedback from clinical experts was continuously incorporated to refine the device's functional, ergonomic, and safety specifications.

### 2.3.1 Clinical Requirements

From a clinical standpoint, the proposed sensorized orthosis must comply with the fundamental safety, comfort, and functionality principles of postoperative rehabilitation. The key clinical requirements include:

1. **Controlled Range of Motion (ROM):** The system must allow therapists to precisely set and adjust flexion/extension limits to prevent hyperextension or excessive flexion during early recovery.

2. **Progressive Load Adaptation:** The device should support gradual load-bearing transitions consistent with rehabilitation stages—from protection to reconditioning—without imposing excessive stress on the tendon.

3. **Joint Stability and Alignment:** The mechanical structure must provide stable, bilateral support to maintain proper joint alignment and minimize unwanted rotational or shear forces.

4. **Long-Term Wearability and Comfort:** The device must be lightweight, ergonomic, and comfortable enough for extended use in both clinical and home-based rehabilitation settings.

5. **Objective Monitoring and Feedback:** Integrated sensing should enable quantitative tracking of joint motion and activity patterns, offering therapists reliable data for progress evaluation and individualized treatment adjustment.

### 2.3.2 Design and Technical Requirements

To meet the clinical objectives mentioned above, the proposed system was developed as a modified extension of the commercially available knee orthosis currently used in hospital practice. The proposed sensorized orthosis design preserves the complete mechanical functionality of the original brace, including range-of-motion limitation, medial–lateral stabilization, and secure fixation—while incorporating embedded sensing and data acquisition modules.

Consequently, the entire system must satisfy the following technical design specifications:

1. **Mechanical Modularity:** The sensorized orthosis should adopt a modular architecture that allows seamless reconfiguration between left and right-leg sets, thereby extending its applicability to a wider range of orthopedic conditions while ensuring full mechanical compatibility with standard clinical knee orthoses.

2. **Integrated Multi-Sensor System:** The sensorized orthosis must integrate inertial measurement units (IMUs) and an encoder to capture joint kinematics in real time. The IMUs provide continuous measurements of angular velocity and acceleration, while the encoder offers high-resolution joint angle feedback. The combined sensing system enables comprehensive motion analysis and supports the development of data-driven rehabilitation strategies.

3. **Local Data Logging and Wireless Communication:** The system should

support dual-mode data management by storing all motion data locally on a microSD card for redundancy and transmitting selected information wirelessly for remote monitoring and clinical review. Local data logging ensures data integrity and security during offline sessions, while wireless communication (e.g., Wi-Fi or Bluetooth) enables seamless integration with hospital databases and therapist monitoring platforms. This dual-storage strategy ensures both reliability in data acquisition and flexibility in data accessibility.

4. **Ease of Maintenance and Sanitization:** All structural and electronic components should be easily detachable for cleaning, sterilization, and reuse across multiple patients. The design should allow rapid dismantling of modules to ensure reliable clinical operation.

# 3

# Methods

## 3.1 Selection of the Base Orthosis

The Enovis X-ROM knee brace (see Fig.2.1) was selected as the foundational platform for the proposed sensorized orthosis system due to its proven clinical acceptance, ergonomic design, and high alignment precision with the anatomical knee axis. This model is widely used in postoperative rehabilitation after tendon or ligament reconstruction, and its mechanical frame and adjustable range-of-motion (ROM) limiter have been clinically validated for both safety and comfort. Its bilateral metal frames and polycentric hinge mechanism ensure precise motion alignment, while adjustable straps provide consistent fixation across different limb sizes. Using such a clinically established brace offers several advantages: it preserves the familiarity of therapists and patients, it complies with existing hospital rehabilitation protocols, and it minimizes regulatory risks compared to designing an entirely new exoskeleton structure.

Previous studies have reported that patient adherence and clinical acceptance are closely related to device familiarity, comfort, and ease of integration into existing rehabilitation workflows [17], [18]. Building upon an approved and ergonomically optimized orthosis therefore enhances usability and facilitates clinical translation. In addition, by using a brace that is already registered as a Class I medical device in most regions, the sensing system can be classified as an incremental modification—simplifying both safety validation and potential future certification.

## 3.2 Component Selection

The electronic subsystem of the proposed sensorized orthosis consists of several key components carefully selected for their performance, compatibility, and reliability. Each component plays a distinct role in ensuring accurate sensing, efficient computation, and stable system operation.

1. **Microcontroller Unit (MCU) – FeatherS3 (ESP32-S3)**

   The FeatherS3, based on the ESP32-S3 microcontroller, serves as the central processing unit of the system. It features a dual-core Xtensa LX7 processor with built-in floating-point support, enabling real-time signal processing and sensor data fusion [24]. The board integrates Wi-Fi and Bluetooth 5 connectivity, facilitating wireless data transmission. Its compact form factor, support 3.3v and 5v output, and multiple SPI/I2C/UART interfaces make it highly suitable for multi-sensor embedded systems [25].

2. **Inertial Measurement Unit (IMU) – ICM-42688P**

   Two ICM-42688P sensors are employed to measure the motion of the thigh and lower-leg segments. Each IMU provides six-axis sensing capability (three-axis accelerometer and three-axis gyroscope) with low noise density, temperature compensation, and programmable digital filtering [26]. These features ensure high measurement accuracy and stability during dynamic movements. The compact size of the ICM-42688P allows easy integration into the 3D-printed housings, while its SPI communication interface ensures fast and reliable data transfer to the ESP32-S3.

3. **Rotary Encoder – AMT223B-V**

   The AMT223B-V is an absolute magnetic rotary encoder used to measure the knee joint's angular position with high precision. It provides 12-bit resolution (4096 steps per revolution) and communicates with the controller via an SPI interface, ensuring accurate and stable angle measurement [27]. Mounted concentrically with the knee joint axis, the encoder delivers real-time absolute position feedback, which is crucial for biomechanical analysis and rehabilitation assessment.

4. **Data Storage – Adafruit MicroSD SPI/SDIO Card Breakout Board**

   To support high-frequency data logging, the system employs the Adafruit MicroSD breakout board, which supports both SPI and SDIO interfaces [28]. This board enables high-speed recording of IMU, encoder, and system status data for offline processing and validation. Its 3.3V operation ensures direct compatibility with the FeatherS3 board, while the compact breakout form factor facilitates installation inside the electronic enclosure.

5. **Power Supply – 2000 mAh Lithium-Polymer (Li-Po) Battery**

   A 2000 mAh Li-Po battery powers the entire system, providing several hours of continuous operation under normal load. The battery was selected for its high energy density, lightweight construction, and stable voltage output, which are essential for portable rehabilitation devices. It connects to the FeatherS3's built-in power management system, allowing USB-C recharging and over-discharge protection to ensure long-term safety and reliability.

Together, these components establish a efficient, and scalable hardware architecture capable of supporting real-time sensing, local data storage, and future extensions such as wireless feedback or closed-loop control for intelligent rehabilitation assistance.

## 3.3 Mechanical Structure Design

The mechanical structure of the proposed sensorized orthosis was designed with the primary objectives of achieving lightweight construction, modularity, and mechanical compatibility with standard postoperative knee braces. The design retains the protective and functional features of conventional orthoses while integrating additional sensing and data acquisition modules into a compact ergonomic framework. By preserving the original structure and functions—such as the adjustable ROM limiter and stabilization of the limb, stabilization—the orthosis ensures safe use during tendon or ligament recovery and maintains precise alignment with the anatomical axis of the knee, minimizing potential misalignment or discomfort. An overview of the CAD design is shown in Fig.3.1, which illustrates the integration of sensor and electronic components with the knee brace.

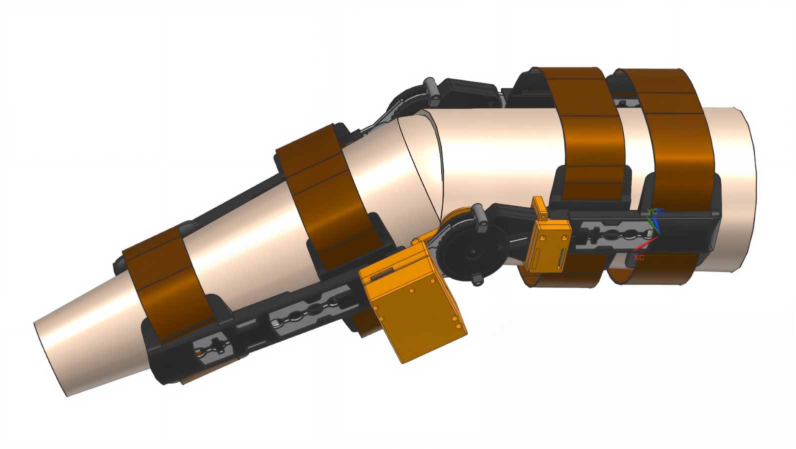


**Figure 3.1:** Overall mechanical structure of the proposed passive knee exoskeleton..

The proposed sensorized orthosis system was developed as a fully independent and non-invasive add-on to the Enovis X-ROM postoperative knee brace, ensuring complete compatibility with its clinical use. All additional modules—including the encoder frame, IMU housings, and electronic enclosure—were mechanically integrated through reversible clamp-type fixtures that require no modification of the original brace, its hinge modules, or the ROM limiting mechanism. Consequently, the underlying brace retains its native geometry, kinematics, and clinical functionality, while the ROM limiter and bilateral hinge mechanisms remain completely operational to ensure joint protection, controlled motion, and mechanical safety throughout postoperative rehabilitation. This design approach minimizes regulatory and clinical risks by preserving validated load paths and safety features of the orthosis, while also eliminating potential confounding factors in gait or rehabilitation assessments that could arise from altered brace mechanics.

To ensure that the integration of sensor modules did not interfere with the mechanical function of the original brace, a kinematic simulation was performed on the modified system. The analysis examined whether the added components restricted the allowable flexion–extension range or altered hinge kinematics. The simulation confirmed that the modified brace maintained the full 0–120° range of motion without mechanical obstruction or interference, demonstrating that the modular sensor attachments preserve the functional integrity of the base orthopedic brace.

A structural comparison was conducted between the original Enovis X-ROM knee brace and the proposed sensorized version to illustrate how the sensing modules were integrated without altering the mechanical or ergonomic characteristics of the base device. In the original configuration, the brace consists solely of the bilateral aluminum frame and adjustable ROM limiter that restrict knee motion within the prescribed rehabilitation range. In contrast, the sensorized version incorporates three modular components:

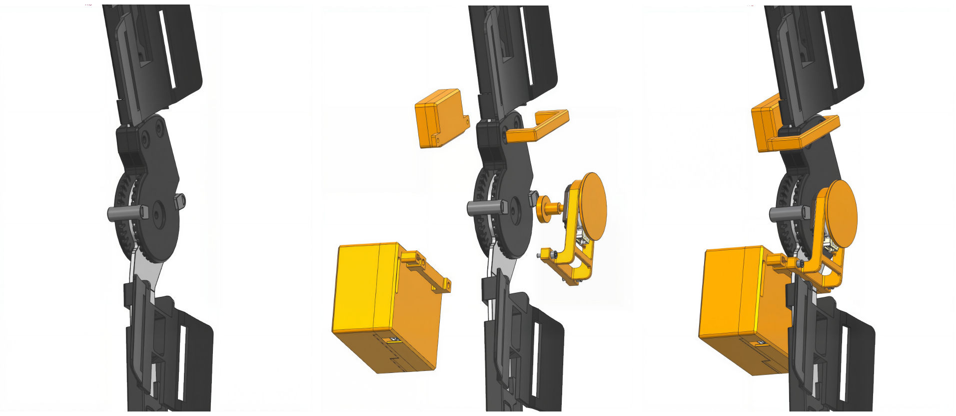
1. A rotary encoder is coaxially aligned with the mechanical knee hinge for precise measurement of the angle of the joint.

2. Two IMUs are used: one mounted on the thigh frame and the other integrated inside the electronic enclosure.

3. The electronic enclosure, mounted on the lateral lower-leg frame, houses the microcontroller, power supply, IMU, and microSD storage module.

**(a)** Base brace **(b)** Exploded view **(c)** Sensorized brace

**Figure 3.2:** Front-view structural comparison between the original orthopedic brace and the proposed sensorized version.



**(a)** Base brace **(b)** Exploded view **(c)** Sensorized brace

**Figure 3.3:** Rear-view structural comparison between the original orthopedic brace and the proposed sensorized version.

As shown in Fig.3.2 and Fig.3.3, the front and rear comparisons clearly illustrate that all sensing modules are externally mounted as modular attachments using reversible clamps and screw fixtures, without any modification to the original brace structure. The exploded views further reveal the compact and non-invasive integration of the encoder, IMU, and electronic enclosure, each positioned away from the motion path of the knee joint to ensure unrestricted movement and user comfort. These visualizations confirm that the sensorized design preserves the geometry, range of motion and alignment accuracy of the base brace while seamlessly incorporating quantitative sensing and data-logging capabilities—achieving complete sensorization without compromising safety, ergonomics or clinical functionality.

To enhance usability and reduce component redundancy, the sensorized orthosis structure is designed for complete left–right interchangeability. This bilateral compatibility is achieved through adjustable fixtures that can be mounted on either side of the brace without affecting alignment with the anatomical axis of the knee. Standardized connectors and positioning features ensure consistent sensor placement, precise reassembly, and reliable operation after repeated installation or maintenance. Moreover, because the sensing modules are mechanically independent and interface through universal clamp-type fixtures, the system can be readily adapted to other knee braces of similar geometry and hinge configuration without structural modification. This design enables rapid configuration, simplifies clinical deployment, and preserves the integrity and functionality of the original brace

To achieve a balance between strength, precision, and manufacturability, all mechanical components were 3D printed using Polylactic Acid (PLA) filament. PLA was selected for its low density, cost-effectiveness, and ease of rapid prototyping, which enabled fast design iteration and high dimensional accuracy. The use of 3D printing technology allows for the quick fabrication of customized parts directly from CAD models, significantly reducing the design–test cycle and facilitating iterative optimization based on mechanical fitting or clinical feedback. This approach makes it possible to rapidly produce and modify prototype structures without the need for expensive molds or machining. Despite being lightweight, PLA offers sufficient rigidity for short-term and experimental clinical evaluation. For future clinical deployment, materials such as carbon-fiber-reinforced nylon (PA-CF) or medical-grade polycarbonate (PC) could be used to further enhance mechanical durability and sterilization compatibility.

In terms of connection design, all major load-bearing joints are reinforced with brass threaded inserts (M2.5 and M3), which are heat-embedded in the PLA structure using a soldering iron to ensure durable screw fastening and repeatable assembly. The entire system uses standard stainless-steel screws (M2.5 and M3) to ensure reliability and corrosion resistance. Each joint is designed for easy tool access, providing sufficient space for maintenance and component replacement while maintaining structural integrity.

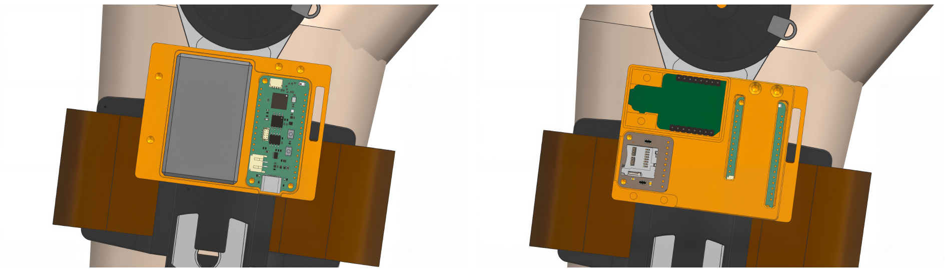
### 3.3.1 Electronic Box

The electronic box serves as the central hub for power management, data recording, and data communication within the sensorized orthosis system. It houses the MCU, the data storage module, and the battery, which together form the control and data acquisition unit of the prototype. The box is designed to provide a secure housing for these electronic components while maintaining accessibility for maintenance and debugging.

From a mechanical perspective, the electronic box is mounted on the outer side of the lower-leg section of the knee brace. This placement was chosen to maintain weight balance and minimize obstruction during walking, thereby reducing discomfort for the user. The housing includes internal mounting points to facilitate secure installation of electronic components, and its rounded-edge design enhances user comfort and safety during use.

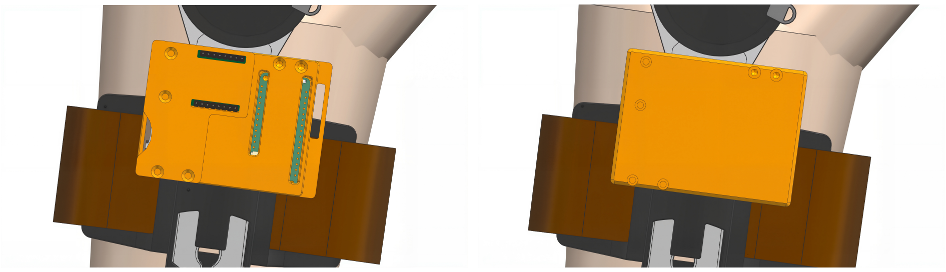
As illustrated in Fig.3.4 and Fig.3.5, the electronic enclosure adopts a multi-layer structural design to ensure organized component placement and efficient use of internal space. The bottom layer accommodates the MCU and battery module, providing a stable foundation and minimizing vibration transmission during movement. The second layer houses the data storage module and the IMU responsible for lower-leg motion monitoring, allowing for efficient data acquisition and storage within a compact layout. The wiring from the encoder and the thigh-mounted IMU is routed through the hollow channel on the right side of the enclosure, as shown in the figure, to minimize external cable exposure and protect the wiring from potential mechanical damage or environmental interference.

The third layer is primarily responsible for routing and securing the electrical wiring of all components, thereby ensuring signal integrity, facilitating maintenance, and protecting against mechanical stress or accidental disconnection. As illustrated in Fig.3.5, which presents both the third wiring layer and the top protective cover, the uppermost cover is designed to fully enclose the electronic components and wiring, providing effective protection against external impact, dust, and environmental interference. This hierarchical structural arrangement significantly enhances the system's reliability, electromagnetic compatibility, and overall assembly efficiency.



**(a)** First Layer **(b)** Second Layer

**Figure 3.4:** Structural layers of the electronic enclosure showing (a) the first-layer internal layout and (b) the second-layer component arrangement..



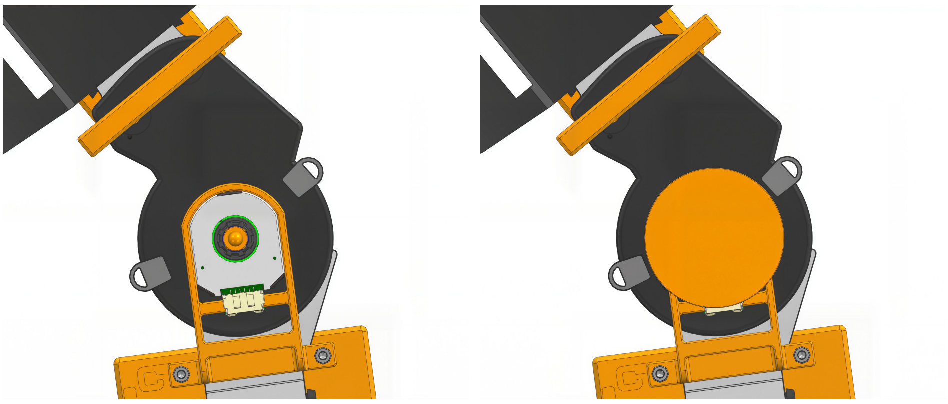
**(a)** Third Layer **(b)** Top Layer

**Figure 3.5:** Structural layers of the electronic enclosure showing (a) the third-layer wiring layout and (b) the top-layer cover assembly.

### 3.3.2 Encoder Frame

The frame of the encoder allows for precise mechanical alignment and secure installation of the rotary encoder for real-time measurement of the angular displacement of the knee joint. Accurate alignment between the encoder shaft and the orthosis hinge axis is critical to obtain reliable angle data. As illustrated in Fig.3.6, which shows the encoder mounted on the brace through the central column and frame, as well as the appearance after attaching the protective cover, the encoder assembly consists of three 3D-printed components: a supporting frame, a central mounting column, and a protective cover. The frame and central column hold the encoder concentrically with the joint axis, ensuring mechanical precision and minimizing alignment error during motion, while the entire assembly is jointly mounted to the knee brace together with the electronic enclosure to form an integrated and stable connection between sensing and structural components.

The protective cover serves as a physical barrier between the electronic components and the user, preventing accidental contact and mechanical impact, thereby ensuring both user safety and component protection. A spherical joint connection between the cover and the central column allows the cover to be adjusted within a limited angular range, allowing flexible positioning to better conform to individual leg contours and improve wearing comfort.



**(a)** Without cover **(b)** With cover

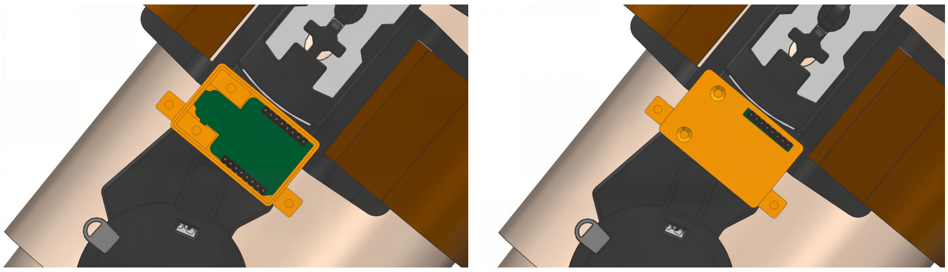
**Figure 3.6:** Encoder Mounting Structure and Protective Cover Assembly of the proposed Sensorized Orthopedic Orthosis.

This structural configuration combines mechanical precision with ergonomic adaptability, ensuring stable angular measurement while maintaining safety, comfort, and ease of use during rehabilitation.

### 3.3.3 IMU Box

Two IMU housings were designed and installed, one in the thigh segment and the other integrated into the electronic enclosure in the lower-leg segment, to measure the relative motion between the upper and lower limbs. Each housing accommodates an IMU, which provides six-axis motion data consisting of three-axis acceleration and three-axis angular velocity. The dual IMU configuration enables accurate estimation of relative orientation, complementing encoder measurements to provide a comprehensive understanding of knee kinematics during rehabilitation exercises. This sensor fusion approach improves the robustness of motion tracking and allows real-time monitoring of dynamic parameters such as flexion–extension rate and limb coordination.

As illustrated in Fig.3.7, which presents the design and installation of the thigh-mounted IMU housing, the upper IMU is enclosed in an independent 3D-printed casing featuring a screw-fastened cover and an internal vibration-damping pad. The damping pad prevents the IMU from shifting or oscillating within the housing during movement, thus maintaining sensor stability and improving measurement accuracy. The cover secures the IMU from external impact while allowing convenient access for inspection or replacement when needed. The housing is mounted to the thigh segment of the brace using a combination of industrial-grade double-sided adhesive tape and a bridge clamp with screws, ensuring both high adhesion and mechanical rigidity. This hybrid mounting strategy guaranties stable sensor positioning throughout dynamic motion, while allowing for easy removal or repositioning without damaging the brace surface.



**(a)** Without cover **(b)** With cover

**Figure 3.7:** Thigh-Mounted IMU Housing Design and Installation on the Proposed Sensorized Orthopedic Orthosis.

The electrical cable connecting the thigh IMU to the electronic box is routed along the side of the brace and protected by a flexible telescopic sleeve, which effectively prevents fatigue due to bending, mechanical wear, and accidental pulling during knee flexion and extension. This configuration minimizes external cable exposure, maintaining a clean and robust appearance consistent with ergonomic design principles. The lower-leg IMU is directly integrated within the electronic enclosure, simplifying wiring and ensuring synchronized data acquisition with the encoder and control unit.

## 3.4 Electronic System Design

The electronic system of the proposed sensorized orthosis was designed to provide accurate motion detection, real-time data acquisition, and stable power management within a modular framework. The overall architecture is illustrated in Fig.3.8, which consists of three major subsystems: the sensing module, the control and processing unit, and the data storage module. All components are interconnected through the MCU, which forms an integrated platform for biomechanical data collection and analysis.

All components are interconnected through the MCU, forming an integrated platform for biomechanical data collection and analysis. The system employs two IMUs to capture the motion of the thigh and shank segments, respectively. Both IMUs share a common SPI interface to optimize the wiring and ensure synchronized data sampling.

In parallel, the encoder and the data storage module operate on a separate SPI interface, preventing data transmission conflicts and maintaining consistent read/write performance during continuous logging. The system also incorporates efficient power regulation circuits to supply stable 3.3 V and 5 V outputs for the sensors and the MCU. This configuration minimizes interference between subsystems while maintaining low latency and high data integrity during real-time acquisition.

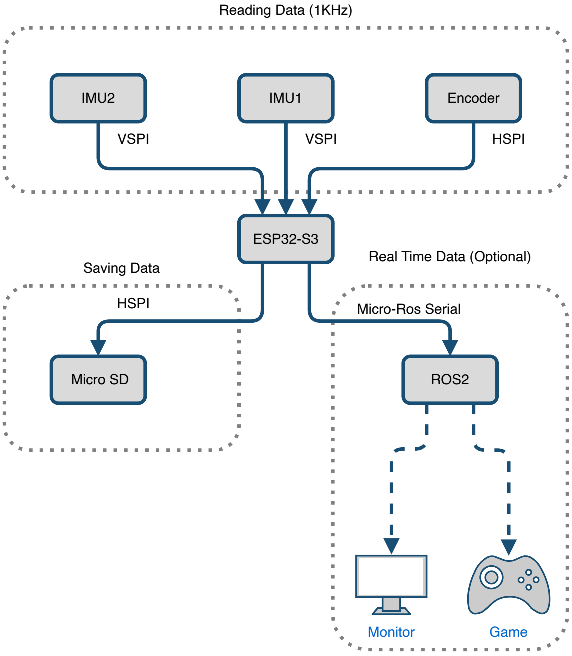


**Figure 3.8:** Electronic System Architecture of the Proposed Sensorized Orthosis.

### 3.4.1 Sensing Module

The sensing module includes two IMU units and one rotary encoder, all operating at a sampling frequency of 1 kHz to ensure high-resolution synchronized motion capture. The IMUs are mounted on the thigh and shank segments, respectively, providing six-axis data (three-axis acceleration and three-axis angular velocity) that describe the dynamic movement of each segment of the limb during rehabilitation. The encoder, concentric with the knee joint axis, measures the absolute joint angle through a digital SPI interface, offering drift-free angular position data.

All three sensors are connected to the control and processing unit via SPI communication, enabling fast, low-latency data transfer, and synchronized acquisition across the sensing module. This configuration provides complementary segment- and joint-level kinematics, supporting accurate motion reconstruction, real-time monitoring, and quantitative evaluation of rehabilitation progress.

### 3.4.2 Data Storage Module

The microSD card board serves as the external data storage unit for all recorded sensing signals. Communicates with the control and processing unit through an SPI interface, enabling stable and continuous data logging of synchronized IMU and encoder measurements. Although the sensors operate at a sampling frequency of 1 kHz, the control system aggregates the collected data and writes them to the data storage module every half second, balancing data resolution with storage efficiency and power consumption.

The board also supports a high-speed SDIO interface, which can be utilized in future upgrades to increase data throughput or enable real-time streaming applications. This configuration ensures long-term reliability while maintaining flexibility for future system expansion and higher-performance data management.

### 3.4.3 Control and Processing Unit

The control and processing unit forms the core of the electronic system and is responsible for managing data acquisition, preprocessing, and communication. The MCU acts as the central node, collecting synchronized signals from the IMU units and the encoder through SPI interfaces. After performing basic preprocessing, such as filtering, time stamping, and data packaging, the MCU writes the processed data to the data storage module for long-term recording and offline analysis.

When connected to an external device, the MCU can also transmit data in real time to a host computer running the ROS2 framework, where the information can be further utilized for visualization, analysis, or interactive applications such as serious games for rehabilitation. The MCU operates in the micro-ROS environment, enabling seamless integration with the broader ROS2 ecosystem. This architecture allows the entire system to function as a unified ROS2 node network, facilitating scalable upgrades, modular extensions, and future incorporation of additional sensors or intelligent control algorithms.

### 3.4.4 System Calibration and Synchronization Validation

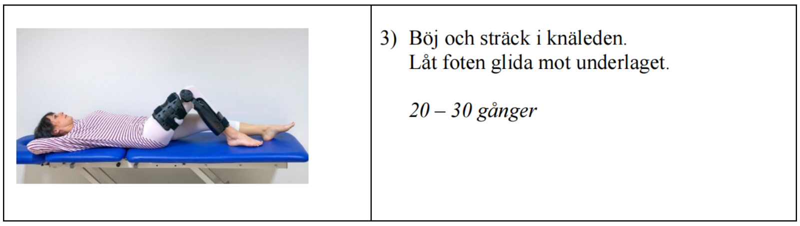
Before experimental data collection, a series of calibration and synchronization procedures were conducted to ensure the accuracy and consistency of the sensing system. The rotary encoder was calibrated using software-based reference alignment, where the knee joint was positioned at full extension (0°) and the corresponding encoder reading was set as zero reference using SPI commands. The encoder output was further validated by data-driven analysis of continuous flexion–extension cycles, confirming linearity and repeatability throughout the full range of motion (0–120°).

Both IMUs were subjected to static and dynamic calibration procedures implemented in software to remove bias and scale factor errors in the accelerometer and gyroscope signals. To synchronize all sensing modules, a firmware-based timing protocol was used, assigning timestamps from a unified system clock to each data packet. The effective sampling rate and timing stability were verified through timestamp analysis of the recorded data, confirming consistent acquisition at 1k Hz.

These validation steps ensured reliable temporal alignment and multi-sensor fusion performance, establishing the measurement accuracy required for subsequent motion analysis and rehabilitation experiments.

## 3.5 Experiment Design

To evaluate the proposed ability of the sensorized orthosis to distinguish between correct and incorrect rehabilitation movements, an experimental was designed based on a clinical rehabilitation protocol obtained from the Sahlgrenska University Hospital (Fig.3.9). This hospital protocol defines the standardized postsurgical knee rehabilitation exercises commonly prescribed for patients recovering from ligament or tendon injuries. From this program, a representative knee flexion–extension exercise was selected as the testing basis, as it is one of the most fundamental and clinically relevant motions to assess knee joint recovery. Movement emphasizes controlled range of motion (ROM), smooth transitions, and stable posture.



3) Böj och sträck i knäleden.
Låt foten glida mot underlaget.

*20 – 30 gånger*

**Figure 3.9:** Extract from the Sahlgrenska University Hospital rehabilitation protocol used as reference for the motion tests.

All three types of motion used in this study were derived from a single rehabilitation exercise consisting of one correct form and two incorrect variants intentionally modified. These motions were designed to represent a progressive scale of rehabilitation quality, allowing the evaluation of whether the exoskeleton's sensing system, which integrates encoder and IMU data, can accurately detect deviations from ideal movement performance.

1. **Supine flexion–extension (Standard form)**
   - performed while lying on the back, without weight bearing.

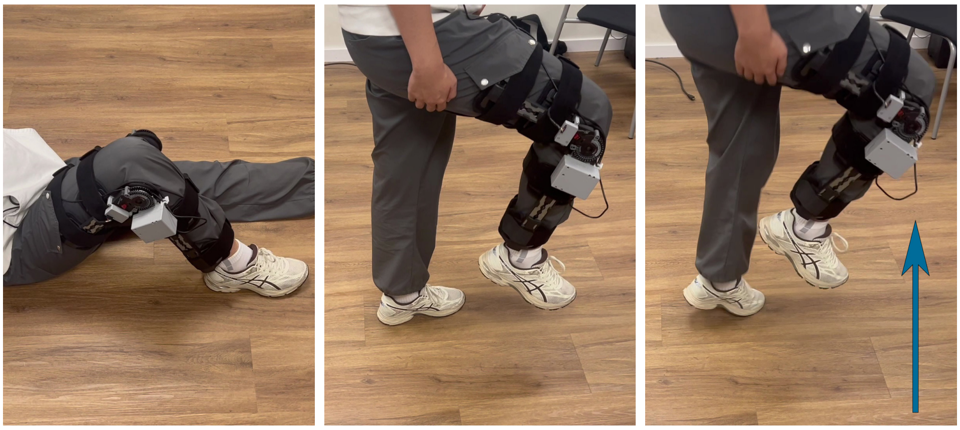
   This represents the standard rehabilitation movement prescribed in the hospital protocol, characterized by controlled speed, smooth movement, and minimal interference by external forces. It served as a baseline for comparison (see Fig.3.10a).

2. **Standing flexion–extension (Partially incorrect form)**
   - performed in standing posture.

   In this variant, weight-bearing and balance oscillations introduce instability and uneven loading of the knee joint. Although visually similar to the correct exercise, the dynamic patterns differ, making it useful to evaluate the system's sensitivity to subtle deviations (see Fig.3.10b).

3. **Semi-flexed jumping (Incorrect form with impact)**
   - executed with a semi-flexed knee followed by a light jump.

This deliberately introduces impact and abrupt dynamic forces, which represent a movement that is not suitable for rehabilitation. It serves as a stress test for the ability of the sensing system to capture rapid acceleration peaks (see Fig.3.10c).



**(a)** Supine Motion **(b)** Standing Motion **(c)** Jumping Motion

**Figure 3.10:** Experimental motion types derived from the standard clinical rehabilitation protocol.

By analyzing and comparing the encoder and IMU data collected from these three types of motion, the experiment aims to verify the system's capability to differentiate between safe and unsafe rehabilitation behaviors. This experimental setup also provides a foundation for the future integration of machine learning-based motion assessment and real-time feedback systems.

# 4

# Results and Discussion

## 4.1 Hypothesis and Rationale

The central hypothesis of this research is that integrating dual IMUs and an absolute encoder into a conventional postoperative knee brace enables precise, quantitative monitoring of rehabilitation motion quality without compromising the mechanical characteristics or usability of the base orthosis. It is further hypothesized that this sensorized design can effectively distinguish between correct and incorrect rehabilitation movements, laying the foundation for intelligent, data-driven rehabilitation feedback in future applications.

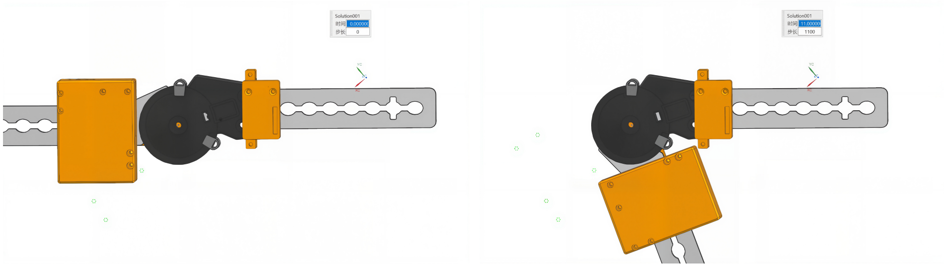
The following sections present the experimental evidence that validates this hypothesis, interpret the results in comparison with related work, and discuss the broader implications and limitations of the proposed system.

## 4.2 Prototype Validation and Evidence

### 4.2.1 Mechanical Integration and Feasibility

The prototype of the passive knee exoskeleton was successfully fabricated and assembled based on the finalized CAD design and 3D-printed mechanical components. All structural parts, including encoder frame, IMU housings, and electronic enclosure, were printed using PLA filament with a 30% infill density to ensure mechanical rigidity and dimensional accuracy. The modular structure allowed rapid assembly and disassembly, as well as complete interchangeability between the left and right sides of the brace without affecting alignment or functionality. The completed prototype maintained full compatibility with a standard postoperative knee orthosis, confirming the adaptability of the proposed design for clinical application (see Fig. 4.2).

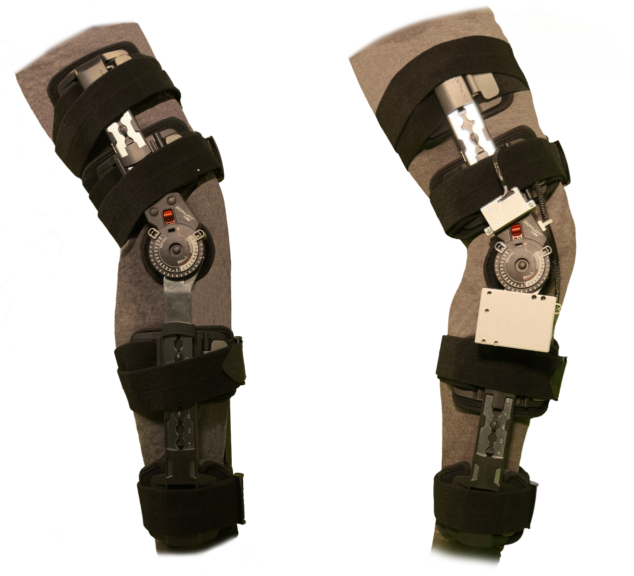
To ensure that integration of sensor modules did not interfere with the mechanical function of the original brace, a kinematic simulation was performed on the modified system. The analysis evaluated whether sensor attachments affected the allowable range of motion of the brace. As shown in Fig.4.1, the modified brace achieved the full operating range of the original system (0 to 120°) without any mechanical obstruction or component interference. These results confirm that modular sensor attachments preserve the functional integrity of the base orthopedic brace.



**(a)** Full extension at 0°. **(b)** Maximum flexion at 120°.

**Figure 4.1:** Kinematic simulation of the Sensorized Orthosis.

In addition to simulation, physical range-of-motion (ROM) tests were conducted using the assembled prototype. The knee joint was repeatedly flexed and extended throughout its full motion range, and the measured ROM remained consistent at 0 to 120° before and after sensor integration, indicating that the added components did not restrict movement or introduce additional mechanical resistance. The total system weight of approximately 180 grams ensured lightweight wearability and minimal added inertia during rehabilitation exercises.



**(a)** Original **(b)** Sensorized

**Figure 4.2:** Comparison Between the Original Knee Orthosis and the Sensorized Version.

### 4.2.2 Sensing Performance and Data Reliability

The encoder and dual IMUs achieved a synchronized sampling rate of 1 kHz, with the Microcontroller Unit (MCU) writing the aggregated data to microSD storage every 0.5 seconds. Testing confirmed that the recorded dataset exhibited no frame loss or temporal drift, fully validating the robustness of the SPI communication and reliable time alignment. Furthermore, the actual communication frequency between the MCU and ROS 2 stabilized at approximately 800 Hz, which lays a solid foundation for the subsequent development of real-time intelligent algorithms within the ROS 2 framework.

During repetitive flexion–extension trials, the encoder produced smooth angular waveforms with consistent amplitude and frequency, while IMU acceleration signals from the thigh and shank segments showed synchronized dynamics and low noise. These results confirm that the system achieves its intended performance in synchronization accuracy, mechanical stability, and sensing precision.

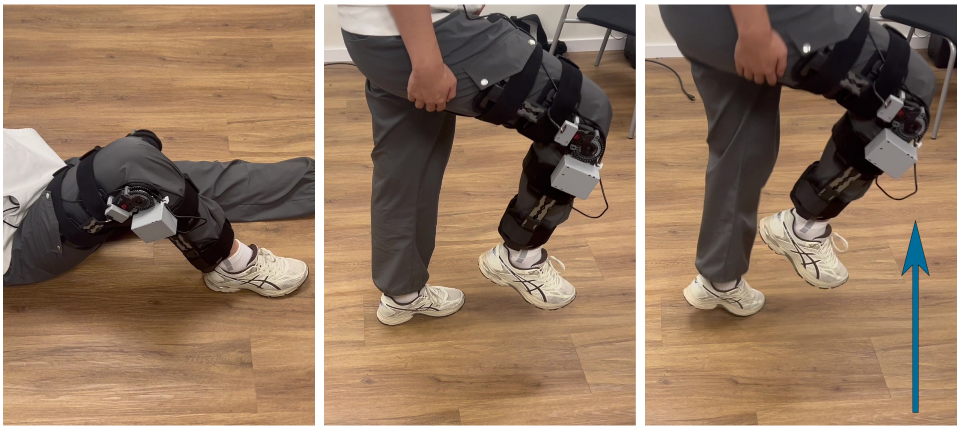
## 4.3 Experimental Evidence for Motion Differentiation

To assess the system's ability to recognize differences in movement quality, three types of motion were performed according to a standardized clinical protocol:

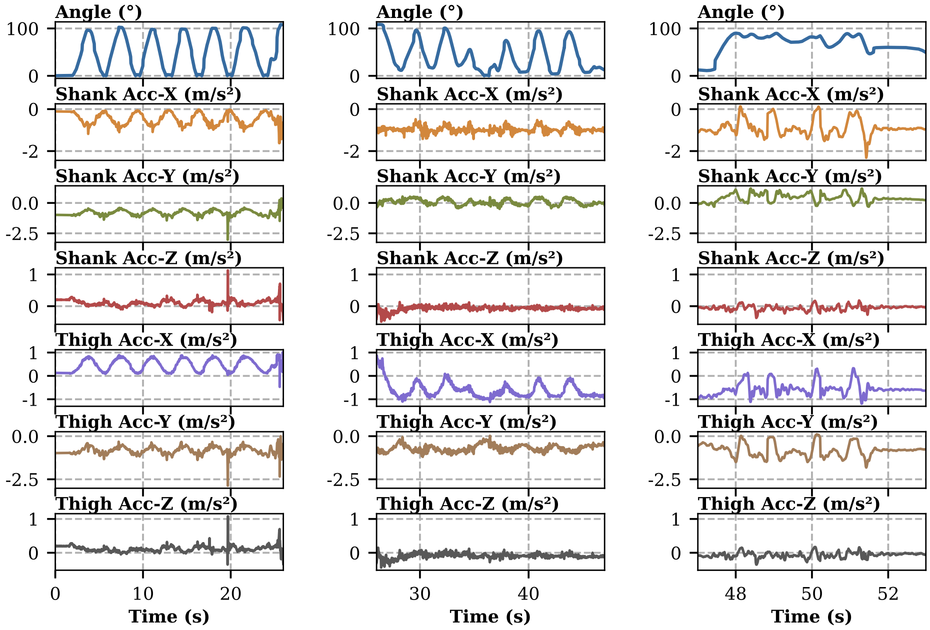
1. **Supine flexion–extension** (correct movement), see Fig4.3a.
2. **Standing flexion–extension** (partially incorrect), see Fig4.3b.
3. **Semi-flexed jumping** (incorrect with impact), see Fig4.3c.

Fig.4.3 illustrates the three representative rehabilitation tasks and their corresponding segmented data samples. The upper row shows the actual motions—supine, standing, and jumping—while the lower row presents the signal segments extracted directly from the red, yellow, and blue highlighted regions in Fig.4.4, which correspond to the supine, standing, and semi-flexed jumping phases, respectively.

Fig.4.4 shows the time-series of joint angle (encoder) and dual-IMU acceleration signals recorded under the three motion conditions. The encoder consistently measured smooth angular trajectories with a stable range of motion (ROM) between approximately 80° and 100° throughout all trials. This observation validates the reliability and precision of the encoder and confirms that the mechanical integration of the sensing modules does not interfere with the natural joint movement of the brace. However, because the angular amplitude and periodicity were nearly identical across the three movements, the encoder signal alone provided limited discriminatory power in distinguishing the correct versus incorrect motion execution.



**(a)** Supine Motion **(b)** Standing Motion **(c)** Jumping Motion



**(d)** Segment-1 (red) **(e)** Segment-2 (yellow) **(f)** Segment-3 (blue)

**Figure 4.3:** Comparison of rehabilitation motion types and their corresponding sensor data segments.

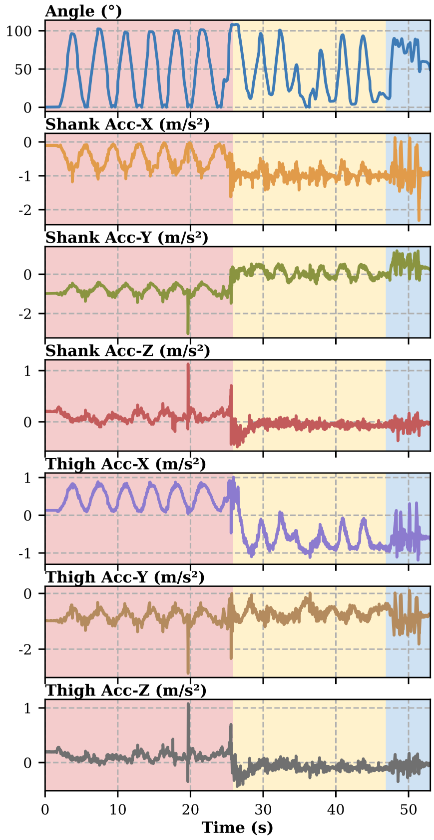


**Figure 4.4:** Measured time-series of joint angle and dual-IMU accelerations under three rehabilitation motion types: supine flexion–extension (red), standing flexion–extension (yellow), and semi-flexed jumping (blue).

In contrast, the dual-IMU signals revealed distinct kinematic and dynamic signatures corresponding to each movement type.

- **Supine flexion–extension (red region):**

  During the supine flexion–extension motion (see Fig.4.3a), the dual IMUs were oriented such that the X-axis pointed vertically toward the ground, the Y-axis aligned along the thigh–shank axis, and the Z-axis pointed laterally outward.

  Throughout the repetitive flexion–extension cycles, the acceleration signals of both the X and Y axes from the dual IMUs exhibited smooth periodic sinusoidal variations, which clearly correspond to the primary sagittal-plane knee motion. Concurrently, the Z-axis acceleration remained within a relatively constant, low-amplitude range, indicating minimal lateral or torsional movement (see Fig.4.3d and Fig.4.4).

  These low-frequency, synchronized waveforms confirm the stability and controlled nature of the flexion–extension motion. It is noteworthy that extremely brief spikes appeared in the Y-axis and Z-axis accelerations, which can be attributed to an accidental impact of the system with the ground during testing. This phenomenon powerfully demonstrates the capability of the sensing system to precisely capture transient external disturbances.

- **Standing flexion–extension (yellow region):**

  In the upright position (see Fig.4.3b), the sensing signals captured the main flexion-extension dynamics under partial weight-bearing conditions. Specifically, the X-axis and Y-axis signals of the upper limb IMU (Thigh) were the dominant components in the signals.

  It is noteworthy that during the flexion–extension transition phase (see Fig.4.3e and Fig.4.4), significant baseline drifts appeared across multiple axes of the dual IMUs (such as the X and Y axes of the lower limb IMU and the X axis of the upper limb IMU). This accurately reflects the subtle changes in vertical loading and the redistribution of the Center-of-Mass between the motion phases. Concurrently, the Z-axis signal displayed minor oscillations associated with lateral balance adjustments.

  These signal variations fully demonstrate the capability of the sensing system (particularly the IMUs) to effectively and accurately capture complex biomechanical information, including loading, posture adjustment, and Center-of-Mass shifts, thereby laying a multi-dimensional, quantitative data foundation for subsequent motion classification and intelligent assessment.

- **Semi-flexed jumping (blue region):**

  In this task (see Fig.4.3c), the leg instrumented with the IMUs remained semi-flexed and weight-bearing, while the contralateral leg performed the jump.

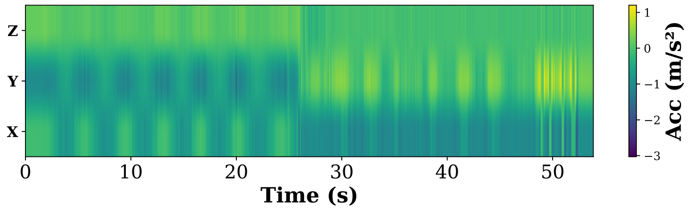
Consequently, both IMUs primarily recorded pronounced high-frequency vibration spikes on the X-axis, with the Y-axis signals also accompanied by smaller high-frequency oscillations. These signals originated from the vertical impact transmitted through the supporting leg during the contralateral limb's take-off and landing, with the force resolving into components simultaneously acting on the X and Y axes of the IMUs (see Fig.4.3f and Fig.4.4). The Z-axis signal, in contrast, remained largely stable.

It is noteworthy that, compared to the sharp impulse signals observed during the supine flexion–extension motion (caused by hard impact with the ground), the impact signals in the jumping task were relatively smooth in amplitude, and the sharpness was significantly reduced. This is mainly because the impact force undergoes natural damping and filtering as it is transmitted through the soft tissues and joint structures of the human body to the sensors, converting the impact pulse into high-frequency vibration.

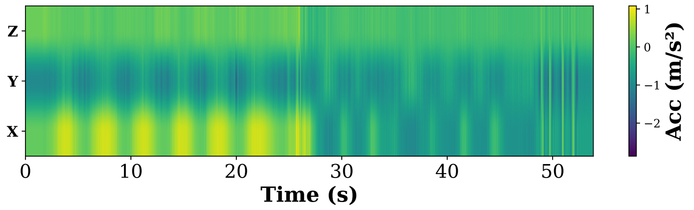
This divergence in signal characteristics indicates that the system is capable of distinguishing, to a certain extent, between impacts to the human body and external impacts directly applied to the system.

Overall, these characteristics not only highlight the system's sensitivity to external impact forces but also affirm its capability to differentiate between active and passive dynamic responses during asymmetric lower-limb activities.

Fig.4.5 further visualizes these differences using three-axis acceleration heat maps from both the shank-mounted and the thigh-mounted IMUs. The color intensity represents the acceleration level along the X, Y, and Z axes. Together, the two IMUs clearly show the progression from low-frequency, smooth motion during the supine phase to mild postural instability and cross-axis coupling in the standing phase, and finally to short, high-frequency bursts during the semi-flexed jumping phase. This dual-IMU visualization provides an intuitive view of how lower-limb motion dynamics evolve—and becomes less controlled—as the rehabilitation task deviates from the ideal execution pattern.



**(a)** IMU Shank



**(b)** IMU Thigh

**Figure 4.5:** Heatmaps of Tri-Axial Accelerations from Dual IMUs.

Collectively, these findings fully demonstrate that while the encoder provides highly stable and accurate angular measurements, the inclusion of dual IMUs enables the extraction of rich temporal and dynamic features crucial for movement quality assessment.

Specifically, the fusion of joint angle and acceleration data forms a multidimensional representation of joint kinematics and dynamics—capable of comprehensively capturing aspects such as smoothness, impact level, and postural stability. This multidimensional sensing approach, in turn, lays a solid foundation for the development of intelligent, quantitative rehabilitation assessment methods.

Furthermore, the experimental results powerfully prove the feasibility of applying this sensorized orthosis framework to clinical monitoring and intelligent rehabilitation supervision.

## 4.4 Game-Based Interactive Rehabilitation

To validate the feasibility and vast potential of the system in the field of intelligent, interactive rehabilitation, the sensing system was integrated via the ROS 2 framework into a Unity3D game platform designed for orthopedic knee rehabilitation [29]. The system streamed real-time knee angle and IMU data from the microcontroller to the host computer, where the Unity engine translated them into interactive virtual visualization content.

In this prototype implementation, the user controls the vertical position of a virtual ball by precisely performing knee flexion and extension (as illustrated in Fig.4.6). The virtual ball moves forward through a tunnel composed of green obstacles, requiring the user to accurately adjust their motion trajectory to guide the ball through the openings. This design successfully transforms repetitive, monotonous rehabilitation exercises into an immersive interactive activity demanding precise movement control and accurate timing.

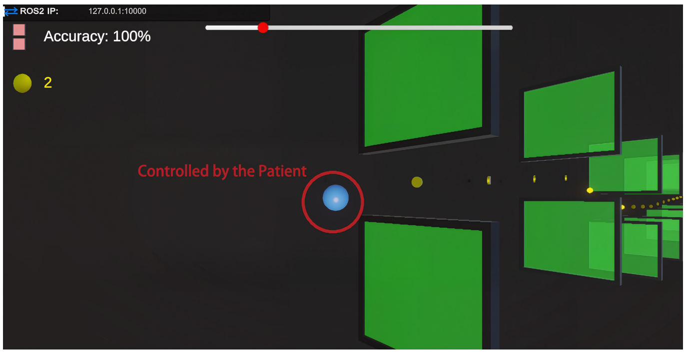


**Figure 4.6:** Unity-based obstacle-avoidance rehabilitation game controlled by knee motion.

Clinicians can implement personalized adjustment of the game's difficulty according to the patient's rehabilitation stage by modifying the limits of Range of Motion (ROM) and the forward speed of the virtual ball.

As illustrated in Fig.4.7, the interface intuitively allows clinicians to specify the minimum and maximum knee flexion angles and select among three speed settings (Slow, Normal, Fast).

For users in the early rehabilitation stage: the system assigns smaller ROM ranges and lower speeds, aimed at strictly controlling loading and preventing secondary injury.

Conversely, for users in the later rehabilitation stage: they can utilize a larger Range of Motion and faster movement speed for training, thereby effectively supporting the comprehensive recovery of muscle strength and advanced motor control capabilities.

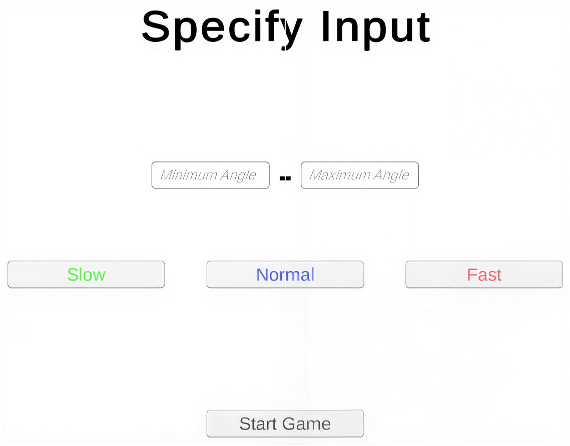


**Figure 4.7:** Difficulty selection interface of the Unity-based rehabilitation game.

This seamless integration of biomechanical sensing with Unity-based interactive visualization not only strongly demonstrates the feasibility of combining low-cost embedded sensing technologies with interactive digital rehabilitation systems, but also fully showcases the immense potential of this system in the field of intelligent, interactive rehabilitation, aligning with contemporary trends in smart rehabilitation development.

## 4.5 Interpretation and Comparative Discussion

The results demonstrate that the proposed system successfully bridges the gap between mechanical safety and intelligent rehabilitation. Traditional knee braces provide joint stability but lack sensing, monitoring, and feedback capabilities, whereas robotic exoskeletons offer advanced sensing and active assistance at the cost of high complexity and limited clinical practicality. Existing sensorized knee braces have shown the potential of wearable sensing in orthopedic rehabilitation, but their technical depth and level of clinical validation remain limited. In contrast, the sensorized brace developed in this study preserves the passive, inherently safe mechanical structure of a conventional orthosis while introducing intelligent motion-sensing functionality. This design achieves an optimal balance between safety and smart rehabilitation support, effectively addressing clinical demands for reliable monitoring and data-driven decision-making.

Porciuncula et al. (2018) reviewed wearable IMU-based systems for rehabilitation monitoring and concluded that most relied on single low-frequency sensors with limited synchronization and no joint-specific calibration, restricting their capacity for quantitative dynamic motion analysis [8].

McPherson et al. (2024) validated the Digital Knee brace, a commercial post-operative monitoring system that integrates a clip-on IMU with a cloud platform. Their study confirmed moderate validity for gait-related parameters such as stride length and velocity, but was constrained to 2D gait analysis at low sampling rates and healthy participants in laboratory settings, without direct measurement of joint-angle [15].

Bellitti et al. (2022) developed a smart knee brace for the measurement of static and dynamic laxity, combining two IMUs and three stretch sensors to capture translational and rotational laxities of the knee [16]. Their design effectively supported the Lachman and pivot-shift tests, yet the system operated at 40 Hz, required wired synchronization, and lacked long-term validation under natural rehabilitation motions.

In contrast, the orthosis proposed in this study integrates two IMUs and an absolute rotary encoder, enabling synchronized six-axis motion monitoring and high-precision angle capture during dynamic rehabilitation tasks. Unlike previous prototypes, the device is built upon a clinically approved orthopedic brace, which simplifies regulatory compliance processes while supporting patient comfort and therapist acceptance.

In general, the proposed system bridges the gap between smart clinical braces and research-grade motion capture sets, offering high-resolution, synchronized, and clinically deployable sensing for postoperative knee rehabilitation.

## 4.6 Implications and Limitations of the Proposed System

### 4.6.1 Implications

The results of this study extend beyond the immediate scope of postoperative knee rehabilitation. By combining a clinically accepted passive brace with embedded sensing and interactive feedback, this system demonstrates a new paradigm for intelligent orthotic devices—where simple mechanical supports are transformed into data-rich platforms capable of monitoring, evaluating, and guiding rehabilitation progress in real time.

- **Objective and data-driven rehabilitation metrics**

  The system transforms rehabilitation assessment from traditional subjective observation to sensor-based quantitative evaluation. By combining encoder and IMU data, it provides objective metrics such as joint angle, movement smoothness, and acceleration variability, enabling clinicians to evaluate performance, detect abnormal movement patterns, and support personalized, data-driven intelligent rehabilitation strategies.

- **Application Potential in Intelligent Interactive Rehabilitation**

  The seamless integration of the sensing system into a Unity3D game platform for orthopedic knee rehabilitation via the ROS 2 framework strongly demonstrates the feasibility of combining low-cost embedded sensing technologies with interactive digital rehabilitation systems, and fully showcases the immense potential of this system in the field of intelligent, interactive rehabilitation. The real-time visual feedback mechanism provided by this integration has been shown to effectively enhance treatment adherence, while the precise, repetitive task practice offered by the system further facilitates the process of neuromuscular reeducation [30]-[33].

- **Scalable and modular sensing framework**

  Another key implication lies in the modularity and scalability of the mechanical structure. Sensorized components align with standard orthopedic brace geometries, allowing easy transfer to similar commercial knee braces. This modular design streamlines maintenance and accelerates prototyping.

- **Bridge toward intelligent rehabilitation systems**

  By continuously collecting synchronized motion data, the system establishes a foundation for next-generation intelligent rehabilitation devices. These data can be leveraged for machine-learning–based functions such as movement recognition, error detection, and adaptive difficulty adjustment.

- **Clinical and translational potential**

  Finally, based on an existing clinically approved knee brace, the proposed system provides a practical path to faster regulatory translation and patient acceptance. It preserves the safety and comfort of conventional orthoses while adding advanced sensing and feedback functions, supporting real-world use in hospital, outpatient, and home-based rehabilitation settings.

### 4.6.2 Limitations

Despite promising outcomes and broad potential applications, several limitations should be acknowledged to provide a balanced interpretation of this work and guide future improvements.

- **Limited participant sample**

  The experimental validation was conducted on a healthy subject under controlled laboratory conditions. Whilst this setting suffices for verifying synchronisation accuracy, data integrity and sensor performance, it fails to reflect the variability present in clinical populations and cannot guarantee that the system will exhibit identical performance across different patient cohorts.

- **Restricted task variety**

  The current experiments focused on low-speed flexion–extension and a simple jump-like motion to demonstrate movement differentiation. More dynamic tasks such as walking, squatting, and climbing stairs were not included, which limits the evaluation of the system's performance in functional rehabilitation scenarios.

- **Absence of real-time classification and feedback adaptation**

  Although the system can acquire synchronized high-frequency data, it does not yet implement onboard algorithms for real-time motion quality assessment. All analyses were performed offline, making it difficult to provide immediate data feedback to the user.

- **Material and mechanical durability constraints**

  The prototype was fabricated using PLA through 3D printing, which is suitable for prototyping but limited in mechanical strength, heat resistance, and long-term wearability. These material properties restrict its suitability for extended clinical use.

- **Limited environmental robustness and power optimization**

  All tests were conducted under controlled laboratory conditions without external disturbances. The performance of the system under magnetic interference, temperature variation, or power fluctuations remains unverified.

### 4.6.3 Summary

In summary, the developed sensorized knee orthosis successfully demonstrates how an affordable and modular sensing architecture can transform a conventional orthosis into a quantitative and intelligent rehabilitation tool. Although the current prototype remains at the proof-of-concept stage, its high-precision sensing, modular hardware architecture, and game-based interactive rehabilitation features collectively lay a strong foundation for future AI-driven intelligent rehabilitation systems.

# 5

# Conclusion and Future Work

## 5.1 Conclusion

This thesis presented the design, development, and experimental validation of a novel passive knee exoskeleton intended for orthopedic tendon rehabilitation. The proposed system successfully bridges the gap between conventional postoperative braces and advanced robotic rehabilitation devices by integrating mechanical protection, modularity, and quantitative motion monitoring within a compact and lightweight structure.

The mechanical structure of the system was designed as a fully independent and non-invasive add-on module to an existing postoperative knee brace. This design allows it to accommodate additional sensing and electronic components while preserving the functional integrity and ergonomic comfort of the clinically approved brace.

The structure was fabricated using PLA material through high-precision 3D printing, achieving excellent rigidity, dimensional accuracy, and rapid manufacturability. The final assembly weighed approximately 180 grams, ensuring user comfort and minimizing interference during rehabilitation exercises.

The electronic subsystem, built around the FeatherS3 (ESP32-S3) microcontroller, integrated an AMT223B-V rotary encoder and two ICM-42688P IMUs to achieve high-frequency motion detection. The system supported a hardware-level 1 kHz data acquisition rate while achieving an actual communication frequency of around 800 Hz with the ROS 2 framework. Coupled with multi-sensor fusion and reliable microSD storage, the system not only supports offline analysis but also possesses the potential for real-time applications. Experimental validation confirmed stable data transmission, accurate angular measurement, and clear differentiation between rehabilitation motion patterns, fully verifying the feasibility of the proposed architecture for quantitative rehabilitation motion assessment.

Building on this foundation, an existing Unity3D-based rehabilitation game interface was adapted and integrated into the proposed sensorized orthosis [29]. By mapping sensor data to virtual game dynamics in real time, the system provided immediate visual feedback. This combination of sensor monitoring and interactive feedback showcases the great potential of integrating biomechanical monitoring with usercentered digital rehabilitation approaches.

Beyond prototype validation, the high-resolution dataset collected in this study provides a valuable resource for intelligent rehabilitation assessment and clinical decision support. This high-precision dataset establishes a foundation for the development of intelligent algorithms capable of recognizing rehabilitation movements, evaluating motion quality, detecting anomalies, and helping therapists in formulating personalized rehabilitation plans.

Looking ahead, future work will focus on leveraging this dataset to implement machine learning–based motion recognition and anomaly detection. The introduction of machine learning architectures such as Convolutional Neural Networks (CNN) and Linear Discriminant Analysis (LDA) will help transform the system from a passive monitoring platform into an intelligent rehabilitation assistant capable of providing personalized feedback and optimizing rehabilitation strategies. This data-driven approach to rehabilitation is of great significance for advancing traditional rehabilitation systems from manual supervision toward an intelligent and personalized paradigm.

In summary, this study makes a significant contribution to the field of data-driven rehabilitation, providing novel insights and methodologies for the development of precise and intelligent rehabilitation technologies. This research successfully advances rehabilitation systems from the traditional manual supervision model to the intelligent paradigm of data monitoring and analysis, thereby providing a solid theoretical and practical foundation for the development of intelligent, precise, and personalized rehabilitation technologies.

## 5.2 Future Work

Although the developed sensorized orthosis system has demonstrated promising performance in both mechanical functionality and sensing capability, several aspects can be further improved to enhance its reliability, usability, and clinical applicability. In addition, expanding its validation under various clinical conditions and integrating intelligent features will be essential to realize its full potential. The following directions are proposed for future work:

- **Material Optimization and Durability Enhancement**

  Future versions of the exoskeleton should adopt advanced engineering materials, such as carbon-fiber reinforced nylon (PA-CF) or medical-grade polycarbonate (PC). These materials will significantly enhance the structure's rigidity, fatigue resistance, and long-term durability, while simultaneously meeting sterilization requirements necessary for repeated clinical use and maintaining lightweight characteristics. The application of higher-strength materials will also contribute to optimizing the overall system's structural design, thereby further reducing the device's weight.

- **Low-Latency Wireless Communication via Bluetooth**

  The current system primarily relies on the microSD module for local data logging and utilizes Wi-Fi for real-time communication. However, the existing Wi-Fi link introduces relatively high communication latency, which severely constrains the system's responsiveness in quick-feedback applications and restricts its application in outdoor environments. To address this, the next-generation design will integrate a low-latency communication interface based on Bluetooth, achieving a stable and seamless connection with mobile or desktop applications. This key improvement will strongly support real-time data visualization, remote monitoring, and real-time motion assessment with enhanced responsiveness.

- **Comprehensive Clinical Evaluation and Testing**

  We aim to conduct extensive future tests that involve both patients undergoing tendon or ligament rehabilitation and healthy participants, to evaluate the precision, comfort, and safety of the system in clinical settings. Long-term clinical trials and feedback from physiotherapists will be essential to validate its practical applicability, improve mechanical ergonomics, and optimize intelligent algorithms.

- **Development of a Patient–Therapist Interaction Platform**

  A user-friendly data interaction platform will be developed in the form of a mobile or desktop application to provide visual feedback of the monitoring data and seamless communication between patients and therapists. This platform will enable users to visualize movement data, receive personalized feedback, and track progress, while therapists can remotely evaluate rehabilitation performance and adjust exercise plans accordingly.

- **Integration of Artificial Intelligence for Motion Recognition and Evaluation**

  Future work will incorporate AI-based algorithms to automatically recognize rehabilitation movements, evaluate their correctness, and quantitatively assess motion quality. By analyzing patterns in encoder and IMUs data, machine learning models could provide real-time guidance, error detection, and adaptive feedback, helping patients perform exercises safely and effectively.

- **Design of Rehabilitation-Focused and Patient-Adaptive Interactive Games**

  An important direction for future work is the design of engaging and adaptive game-based rehabilitation interfaces to pioneer more efficient rehabilitation paradigms. By integrating real-time motion data from the exoskeleton, these games can dynamically adjust difficulty levels, movement ranges, and feedback responsiveness, thus transforming repetitive exercises into a highly interactive and personalized rehabilitation experience. We plan to quantitatively evaluate the potential for game-based rehabilitation to improve patient training adherence and ultimate rehabilitation outcomes through rigorous experimental validation.

In summary, these developments aim to transform the current prototype into a fully intelligent, connected and clinically validated rehabilitation system. By integrating stronger materials, wireless communication, AI-driven motion analysis, and an interactive user platform, the proposed sensorized orthosis can evolve into a practical and accessible smart device for personalized orthopedic rehabilitation.

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