Intelligent Embedded Systems Lab

universität freiburg

Embedded Computing Entrepreneurship

Burhan Ali (5866011), Jumshaid Khan (5651236)
Momina Atif Dar (5653072), Muhammad Osama Asghar (5771859)

KneeSense: Rehabilitation for Knee Injuries using Sensorized Orthosis

Date: August 30, 2024
Supervisors: Prof. Dr. Oliver Amft, Jochen Kempfle & Lena Uhlenberg

Abstract

Knee injuries are one of the most common forms of injuries in the world. The report presents our product called **'KneeSense'**, an intelligent orthosis paired with a cross-platform mobile application designed to support knee rehabilitation. We are using Inertial Measurement Units (IMUs) to measure the angle between the thigh and shank, along with temperature sensors to monitor fluctuation in knee temperature during exercises. Unlike existing solutions, KneeSense emphasizes affordability and user engagement and bridges the gap between doctor and patient by allowing remote monitoring and personalized exercise regimens. Our innovation aims to reduce cost, increase effectiveness, and enhance usability in knee rehabilitation, potentially producing faster knee recoveries and saving hours of workload.

Contents

1 Introduction

Problems with knees are widespread among men and women. In the USA alone, approximately 15 to 20% of men and 20% of women suffer from knee pain [1]. There can be various reasons; it can appear due to ageing or accident-related injuries. According to research, knee injuries make up 41% of injuries in the world of sports [2].

Since knee injuries are widespread, there is a need to find an effective yet inexpensive cure or a tool that can lead towards healing. Some existing orthoses are beneficial but often are limited in functionality, have higher costs for healthcare systems, and limit their adoption and long-term effectiveness. To cater to the issues of other solutions, we have worked on a design of orthosis that will help patients perform specific exercises prescribed by their physician and keep track of their progress via an intuitive mobile application. The orthosis is designed with affordability in mind, making it accessible to a broader population. At the same time, the mobile application is crafted by keeping user-friendliness in mind to enhance user engagement.

Our knee orthosis is designed to provide adequate support and comfort for people of all ages, from active teens to elderly individuals. Our focus is on offering reliable support for patients recovering from sports injuries or managing conditions related to ageing, helping them stay active and comfortable.

Figure 1: AM Smart Orthosis
[3]

Figure 1 shows an example of innovative knee orthosis. This orthosis monitors the knee angle and displays the data on an application, but it does not bridge the gap between a Doctor and patient and does not provide any rehabilitation features i.e., exercise monitoring, as we do. Other options are also available in the market, which will be compared with our proposed solution in Sec. 2.

The report outlines the design, development, and testing of the knee orthosis and its accompanying mobile application, highlighting key features, user experience, and the potential impact on patient outcomes. Through this work, we aim to contribute to advancing knee rehabilitation by providing an innovative solution that bridges the gap between cost, effectiveness, and ease of use.

In the following pages, we discuss the related work in Sec. 2, the motivation behind creating an innovative knee orthosis paired with a mobile application in Sec. 3, our market analysis in Sec. 4, our proposed design and implementation of a mobile application in Sec. 5, our results in Sec. 6, and the limitations of our solution and the enhancement that can be made to our solution in the later sections.

2 Related Work

Existing research has explored various aspects of knee orthosis and their integration with mobile technologies to enhance patient outcomes and monitoring.

2.1 Knee Angle Measurement

Measuring knee angles is crucial in areas like biomechanics, rehabilitation, sports science, and orthopedics. Accurate knee angle measurements are essential for evaluating joint function, diagnosing injuries, and tracking rehabilitation progress. Three popular devices used for this purpose are flex sensors, string potentiometers and Inertial Measurement Units (IMUs).

2.1.1 Flex Sensors

Flex ensors are resistive devices that change their resistance when flexed. The resistance of the sensor increases with the amount of flexion. These sensors are typically made from materials like carbon-based ink or conductive polymers.

Flex sensors can be integrated into wearable devices, such as knee braces or straps, to measure the angle of the knee joint. When the knee extends, the sensor extends accordingly, changing its resistance, which can be measured and converted into an angle value as shown in Figure 2.

Flex sensors rely on a change in resistance when bent. With time, the material within flex sensors can go through wear and tear with repeated flexing. This can cause inconsistencies in resistance, leading to less accurate readings or a shorter sensor lifespan.

Figure 2: NeeFlex [4]

2.1.2 String Potentiometers

String potentiometers, also known as string pots or cable-extension transducers, measure linear displacement. They consist of a spring-loaded spool of wire or string attached to a potentiometer. When the string is pulled, the rotation of the spool changes the potentiometer's resistance, which can be converted into a displacement measurement.

In knee angle measurement, a string potentiometer can be attached to the thigh and the shank as shown in Figure 3. As the knee flexes or extends, the string extends or retracts, changing the resistance of the potentiometer. This resistance change is then translated into the knee angle.

String Potentiometers measure linear or angular position through the movement of a string attached to a potentiometer. The mechanical components, such as the string or the potentiometer, can wear out over time. This can cause changes in the resistance or mechanical drift, which in turn causes inaccurate measurements.

Figure 3: Wearable sensor for estimating joint-angles [5]

2.1.3 IMUs

IMUs are used to measure knee joint angles [6] [7] [8] [9] [10] [11] [12]. However, their application presents unique challenges due to the complexity of human anatomy and the arbitrary mounting orientations on the leg.

2.2 Knee Temperature Measurement

After some research [13] [14], we came up with the idea to add the functionality of knee temperature monitoring for doctors. It allows them to observe whether their patients may have some inflammation or whether their exercise is causing abnormal temperature increases in their knee joints.

The authors in [15] did extensive research to compare the temperature of a healthy knee with that of an unhealthy one. The comparison is seen in Figure 4.

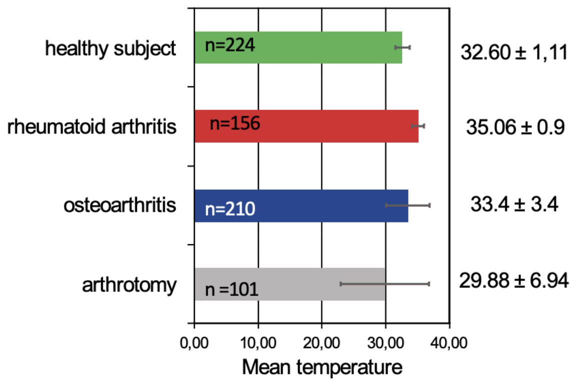


Figure 4: Comparison between healthy and unhealthy knee temperature [15]

2.2.1 Contact Sensor - DS18B20

DS18B20 is a contact sensor that works when it comes in contact with the skin. It measures temperatures from -55°C to +125°C with ±0.5°C Accuracy from -10°C to +85°C [16]. It has a unique 1-Wire interface that requires only one port pin for communication.

2.2.2 Contactless IR Thermopile Sensor - MLX90614ESF

MLX90614ESF is a contactless temperature sensor. It has a low noise amplifier, 17-bit ADC and powerful DSP unit [17]. It measures temperature between -40 to 125°C for sensor temperature and has a measurement resolution of 0.02°C.

2.3 Our Solution

We chose IMUs over string potentiometers or flex sensors for angle measurement in our knee orthosis. IMUs are a more durable and consistent option for long-term use in orthosis.

We decided to work with DS18B20 for knee temperature measurement as it provides direct temperature readings from the skin. Multiple sensors can be easily integrated into an array to improve the design, communicating over a single wire using the one-wire protocol. It simplifies the wiring and integration into the fabric of the knee brace.

On the other hand, MLX90614ESF requires a clear line of sight to the skin, so the accuracy can be affected by the movement of the brace. The sensor needs to be calibrated for the skin's emissivity, typically around 0.95 - 0.98 for precise readings. The line of sight is very regional and limited, necessitating an array of sensors to cover the desired area adequately. Its per-unit cost is also higher than that of DS18B20.

2.4 Comparison with Existing Solutions

2.4.1 OPUM

OPUM Technologies offers the Digital Knee [18], an advanced remote patient monitoring (RPM) system designed specifically for knee health. It is a subscription-based system that utilizes a goniometer-based sensor integrated with the Digital Knee Twin, which creates a digital representation of the patient's knee. The device captures clinical data such as knee range of motion, gait analysis, and daily activity levels, which are analyzed using AI algorithms. They have a mobile application that offers knee rehabilitation exercises that are pre-fed by the developers.

Figure 5: OPUM [18]

2.4.2 OPED

The Orthelligent Knee by OPED [19] is a smart rehabilitation tool designed for outpatient care following knee injuries. It combines a motion sensor and a companion app to monitor and analyze knee movements, providing visual feedback on the healing process. The system allows for comparing the injured knee with the healthy one, offering precise insights into recovery progress. The app guides users through various movement tests, helping doctors and therapists track and adjust rehabilitation plans based on real-time data.

Figure 6: OPED [19]

2.4.3 SKYRE

The Skyre Smart Knee Brace [20], developed by PA Consulting, is an innovative solution that redefines the relationship between patients and physiotherapists. This smart knee brace is designed to provide real-time feedback on knee performance, offering insights to both patients and healthcare professionals. It includes sensors that monitor various parameters such as movement, strength, and alignment, which are then analyzed to support personalized rehabilitation plans. The data can be shared with physiotherapists, enabling remote monitoring and adjustments to treatment protocols.

Figure 7: SKYRE [20]

2.4.4 Sensoria - Smart Knee Brace

The Sensoria Smart Knee Brace [21] is an advanced wearable device designed to monitor and enhance knee rehabilitation. It features integrated textile sensors that track knee range of motion, gait, and muscle activity, providing real-time feedback to users and healthcare providers. The device connects to a mobile app, offering personalized exercise plans, progress tracking, and remote monitoring capabilities. This smart knee brace is intended to improve patient outcomes by facilitating more accurate and adaptive rehabilitation processes.

Figure 8: SKYRE [21]

2.4.5 Our Solution

Our one-time purchase smart knee orthosis is cost-efficient as shown in Figure 9 that goes beyond the features provided by knee braces covered in this section. Our device includes standard monitoring capabilities and the functionality of tracking temperature changes in the knee during exercises, which helps doctors identify potential inflammation, allowing for more targeted and responsive care. Our mobile application bridges the connection between doctors and patients, enabling patients to perform exercises at home while allowing doctors to access and review exercise details remotely. Additionally, our mobile application allows doctors to add customized rehabilitation exercises, tailoring them to each patient's needs. Our solution is a one-time purchase, offering long-term value without ongoing costs.

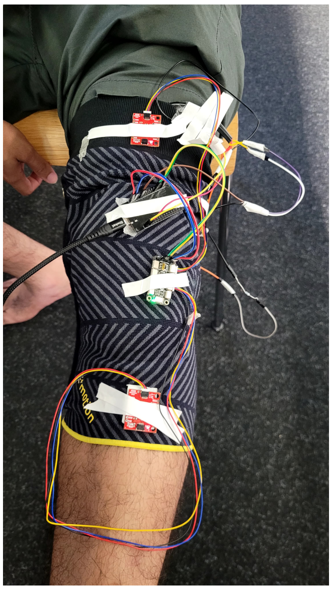


Figure 9: Our smart knee orthosis

3 Motivation

Knee injuries are common in the elderly as well as athletes [22] [2]. It puts a lot of strain on Health Insurance companies in terms of cost as well as patients in terms of availability of rehab centers and facilities. Effective rehabilitation is essential for regaining mobility, reducing pain, and improving the overall quality of life, but it also demands significant time, effort, and financial resources. According to research [23], in a developing country like India around 52% people sought physiotherapy after knee operation or injury but faced difficulties due to high costs related to physical therapy, assistive devices, and follow-up care. These issues are not confined to just one developing country but many others as well. In a developed country like Germany, health insurance covers rehabilitation treatments and it puts a lot of strain on them as well [24]. Hence, it is essential to provide a cost-effective support mechanism for home-based rehabilitation

The aforementioned reasons motivated us to develop a knee orthosis, complemented by an intuitive mobile application, designed to address these specific challenges. By offering an affordable, easy-to-use orthosis coupled with a mobile application that facilitates remote guidance and monitoring, this solution aims to reduce the financial and logistical barriers to effective rehabilitation.

4 Market Analysis

In 2020, there were over 65000 knee injuries in the US alone [25]. In sports, knee injuries are the most common and make up to 41% of injuries [2]. A study [26] shows that knee injuries require more time and care to heal, and the rehabilitation cost can go up to $2000.

Some smart knee orthoses, paired with or without a mobile application, are on the market and can be used for knee rehabilitation. Still, they are costly and are not one-time purchases [18]. It motivated us to develop an inexpensive solution that provides additional features to the users and bridges the gap between doctors and patients. It can save up several hours on both sides and make rehabilitation easier.

In a real-life case study [27] where the patient was fitted with an implant, the authors realized that people living in remote areas could also be facilitated without needing to visit a doctor frequently. It saves a lot of resources on the patient's end. Physicians and healthcare professionals have increasingly recognized the value of knee orthoses, especially when integrated with smart technology for monitoring rehabilitation progress. It is backed by the words of Doctor Ziegler, 'remote monitoring is a major benefit in the rural healthcare setting,' who was the patient's orthopedic surgeon in the case study [27].

According to a report [28], the global knee braces market size is increasing rapidly; by 2031, it is expected to grow to USD 2.6 billion. The rise can be seen in Figure 10. It shows that the target audience is on the rise. The growth is driven by the aging population, increasing incidence of osteoarthritis, and a rise in sports-related injuries. In Europe, Germany holds a significant share of the market.

Figure 10: Knee braces market size [28]

4.1 Target Audience & Marketing Strategy

With an aging population, there's a growing demand for knee orthoses to manage chronic conditions like osteoarthritis. Besides the elderly, our target audience also includes athletes, as knee injuries are prevalent among them, and knee braces are commonly used for prevention and rehabilitation.

We also target physiotherapists in sports franchises, but our solution can be incorporated into the health sector. In the health sector, we will target rehabilitation centers. The orthopedic braces market sees significant demand from rehabilitation centers, hospitals, and orthopedic clinics, where post-surgical recovery and injury prevention are key concerns [28]. We will reach out directly to hospitals and rehab centers and begin with cold emailing to sports franchises.

5 Methods

Our solution consists of a Hardware part and a Software part. The workflow of our solution can be seen in Figure 11 which is described in detail in 5.1.

5.1 System Architecture

The system architecture for the sensorized orthosis, shown in Figure 11 is designed to monitor knee movement and temperature in real-time using a combination of sensors and a microcontroller. At the system's core are two BNO086 IMUs, which we use to calculate the angular rotation of the knee, from their respective quaternions, during exercise and communicate with the ESP32-C3 microcontroller via the I2C protocol. Additionally, two DS18B20 temperature sensors are deployed along the knee, using a one-wire communication protocol that connects all sensors through a single data line. The setup simplifies the wiring and enables efficient polling by the ESP32-C3, which collects and processes the motion and temperature data.

The ESP32-C3 microcontroller, chosen for its robust processing power and wireless capabilities [29], acts as the system's central unit. It gathers sensor data, processes it, and transmits the information wirelessly via Wi-Fi to Firebase, a cloud-based real-time database. A rechargeable battery powers the entire system, with a voltage regulator ensuring stable power delivery to all components. The data stored in Firebase is then accessed by a mobile application, which allows users to monitor the knee's movement and temperature in real-time.

5.2 Selection of Exercises

We have selected a range of basic exercises from a list of strengthening exercises articulated by American Academy of Orthopeadic Surgeons [30].

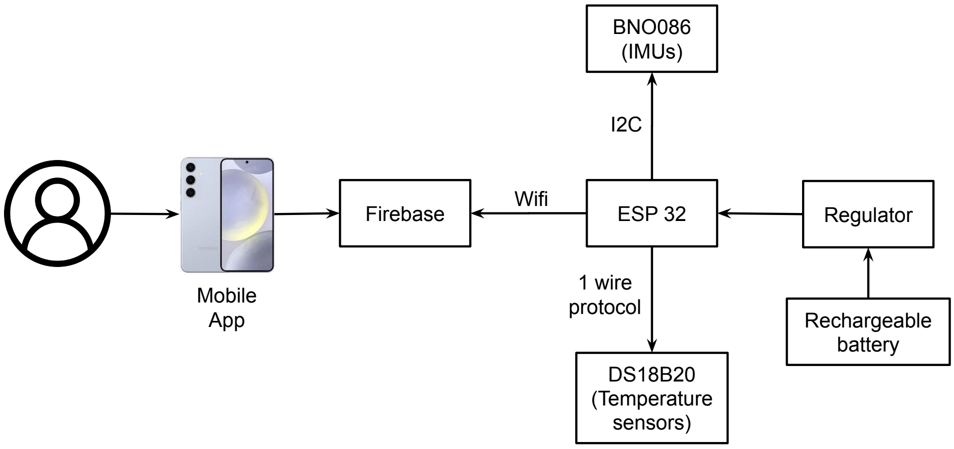


Figure 11: Product workflow

5.2.1 Standing Quadriceps Stretch

Performing Standing Quadriceps Stretch helps to increase mobility, flexibility, and range of motion in the knee and hip joints. [31]. According to a study conducted in [32], performing quadriceps stretch exercise decreased the pain of the subject and improved the physical function. The author also stated that "benefits from exercise can be expected from most patients who follow an exercise program".

To perform it as shown in Figure 12, extend your knee and lift your heel toward your buttock. Using your hand, gently grasp your ankle and pull your heel closer to your body. Maintain this stretch for 30 to 60 seconds, then repeat the process with the other leg.

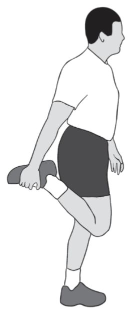


Figure 12: Standing Quadriceps Stretch [30]

5.2.2 Hamstring Curls

Doing Hamstring Curls improves balance and mobility. It strengthens the legs, which lowers the risk of injuries, especially in the knees and lower back [33]. By balancing the strength in the quadriceps (front thigh muscles) and hamstrings, it boosts overall knee health. It makes walking, running, climbing stairs, and standing up from a seat more comfortable.

It increases the strength and flexibility around the knee which is helpful for athletes as it may allow them to keep playing sports, and in non-athletic people it may allow them to avoid surgery [34].

It is performed by holding onto a chair or a wall for balance as shown in Figure 13, then slowly extending the injured knee, lifting the heel toward the ceiling as far as one can without feeling any pain. Holding the position for 5 seconds, then relax. The subject has to repeat this exercise as needed and prescribed by their practitioner.

Figure 13: Hamstring Curls [30]

5.2.3 Leg Extensions

Performing leg extensions improves knee stability. It aids in knee injury recovery by gradually strengthening the quadriceps without putting excessive stress on the knee joint [35]. According to a study conducted in [36], it was observed that performing this exercise increased the gait speed and significantly decreased the pain of subjects in the performing group.

To perform the Leg Extensions exercise as shown in Figure 14, sit up straight on a chair or bench. Tighten the thigh muscles, then slowly straighten and lift the injured leg as high as one can. Hold the position, squeezing the thigh muscles for five seconds. Relax and lower the foot back to the floor, then repeat the exercise.

Figure 14: Leg Extensions [30]

5.2.4 Straight Leg Raise

According to authors in [37], performing straight leg raise exercise strengthens the knee muscles.

To perform the exercise as shown in Figure 15, lie on the floor with elbows positioned directly under the shoulders to support the upper body. Keep the injured leg straight while the other leg is in extension state, placing the foot flat on the floor. Tighten the thigh muscle of the injured leg and slowly lift it six to ten inches off the floor, hold for five seconds, then relax and lower the leg back down. It is to be repeatedly performed as needed and prescribed by the Doctor.

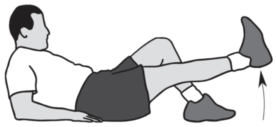
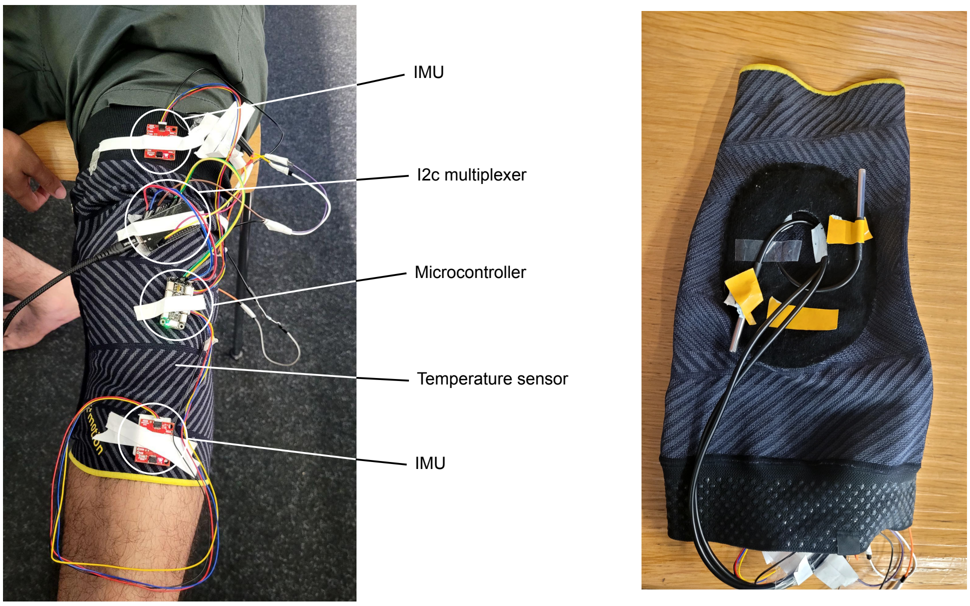


Figure 15: Straight Leg Raise [30]

5.3 Hardware - Smart Knee Orthosis

In this project, we have developed a prototype of a sensorized orthosis, as shown in Figure 16, that monitors knee movement and temperature during exercise. The system uses two Inertial Measurement Units (IMUs) to measure the angle and rotation of the knee, providing insights into joint mobility. Additionally, temperature sensors, as discussed in Section 2, are placed along the knee to map temperature variations, helping to detect potential issues such as inflammation.



(a)

(b)

Figure 16: Exterior of our smart knee orthosis (a) and interior showing temperature sensors (b)

5.3.1 Components Used

- Two IMUs: BNO086

- Controller: ESP32
- Temperature Sensors: DS18B20
- 8 Channel I2c multiplexer

BNO086 IMU: The BNO086 is an IMU from Bosch, chosen for its robust sensor fusion capabilities. It features an inbuilt Dynamic Sensor Bus (DSB) processor that performs sensor fusion internally, outputting unit quaternions that represent the orientation of the knee in three-dimensional space. It simplifies the computational load on the main processor. The BNO086 can communicate via both I2C and SPI protocols, offering flexibility in design and integration.

ESP32 Microcontroller: The ESP32 microcontroller was selected for its powerful processing capabilities and built-in wireless connectivity. This dual-core processor is well-suited for handling the computational tasks required for real-time data processing from the IMUs and temperature sensors. Additionally, the ESP32's ability to form Wi-Fi and Bluetooth connections makes it ideal for transmitting data wirelessly to a user interface, enabling remote monitoring of the orthosis.

DS18B20 Temperature Sensors: The DS18B20 temperature sensors were chosen for their high sensitivity and ease of integration. These sensors communicate via a one-wire bus, allowing multiple sensors to be connected and read through a single data line. This feature reduces wiring complexity and enables the orthosis to monitor temperature at various points along the knee with minimal hardware.

PCA 9548 8 Channel I2C mutiplexer: The PCA9548 is an 8-channel I2C multiplexer/switch that allows multiple I2C devices to share a single I2C bus. It enables communication with up to 8 separate I2C buses from one master I2C bus, solving issues like address conflicts and bus capacity limitations. This device is particularly useful in systems where multiple I2C devices need to be connected but have conflicting addresses or when the number of devices exceeds the capacity of a single I2C bus. It operates at voltages from 2.3V to 5.5V, making it compatible with various logic levels. The PCA9548 uses standard I2C protocol, supports speeds up to 400 kHz, and is available in small form factor packages, making it ideal for applications in servers, telecom equipment, consumer electronics, and industrial control systems.

5.3.2 Placement of sensors

The placement of IMUs was done following the current literature. Studies [5] [11] [10] [38] were found where IMUs proved to be working for knee angle measurement ideally when placed on thigh and shank as shown in Figure 17. Another study [39] was conducted to compare the performance of IMUs placed on the anterior and IMUs placed on the posterior; the authors found that the IMUs placed on the anterior performed better, and the ones placed on the posterior may be interfered with if patient flexes their knee in such a way that their thigh comes in contact with their calf muscle.

The position of IMU should be lateral to the thigh, typically on the midpoint between the hip and knee joints [5]. It should be aligned with the long axis of the thigh, with the sensor's X-axis pointing toward the knee and the Y-axis perpendicular to the sagittal plane. On shank, the position of IMU should be lateral to the shank, typically at the midpoint between the knee and ankle joints. The IMU must be aligned with the long axis of the shank, with the sensor's X-axis pointing toward the ankle and the Y-axis perpendicular to the sagittal plane.

Figure 17: Placement of IMU sensors [12]

In our solution, we strategically placed the temperature sensors on the knee patella after thorough research [38] and analysis.

5.3.3 Firmware Development

The firmware for the sensorized orthosis was developed using the Arduino IDE, chosen for its simplicity and compatibility with the ESP32 microcontroller. The hardware architecture incorporates of a main ESP32 processor with I2C multiplexer to communicate with two BNO086 IMUs, whose sensor fusion protocol hub complicates the direct connection of multiple IMUs to a single I2C bus with different addresses. Therefore, an I2C multiplexer is required for managing the IMU data.

The processor polls for data from both the IMUs and DS18B20 temperature sensors. The processor performs the calculation to extract the angle between orientations of the two IMUs. The processor after gathering and processing data pushes it to Firebase. The mobile application retrieves this data.

To determine the relative orientation between the knee and shank, represented by two quaternions **q1** (thigh) and **q2** (shank), we can calculate the angle directly using the dot product of these quaternions [40].

Dot Product of Quaternions:
The dot product of two quaternions

$$q_1 = (w_1, x_1, y_1, z_1)$$

and

$$q_2 = (w_2, x_2, y_2, z_2)$$

is given by:

$$q_1 q_2 = w_1 w_2 + x_1 x_2 + y_1 y_2 + z_1 z_2$$

The scalar value relates to the cosine of the angle between the two quaternions.

Computing the Relative Angle: The angle θ between the two orientations is calculated as:

$$\theta = 2 * cos^{-1}(q_1.q_2)$$

θ represents the relative rotation angle between the knee and shank segments.

5.4 Mobile Application - 'KneeSense'

While developing the application, we had a vision in mind, to have a user-friendly interface for both Doctors and patients where Doctors can check up on their patients' progress without needing patients to visit them. Patients on the other hand always have instructions to perform their exercises on the go and can have their Doctor keep track of their progress without the need to leave their homes. Our application bridges the gap between Doctors and patients and the user-friendliness of interface ensures that people with non-technical backgrounds can also operate it.

5.4.1 Doctor's end of application

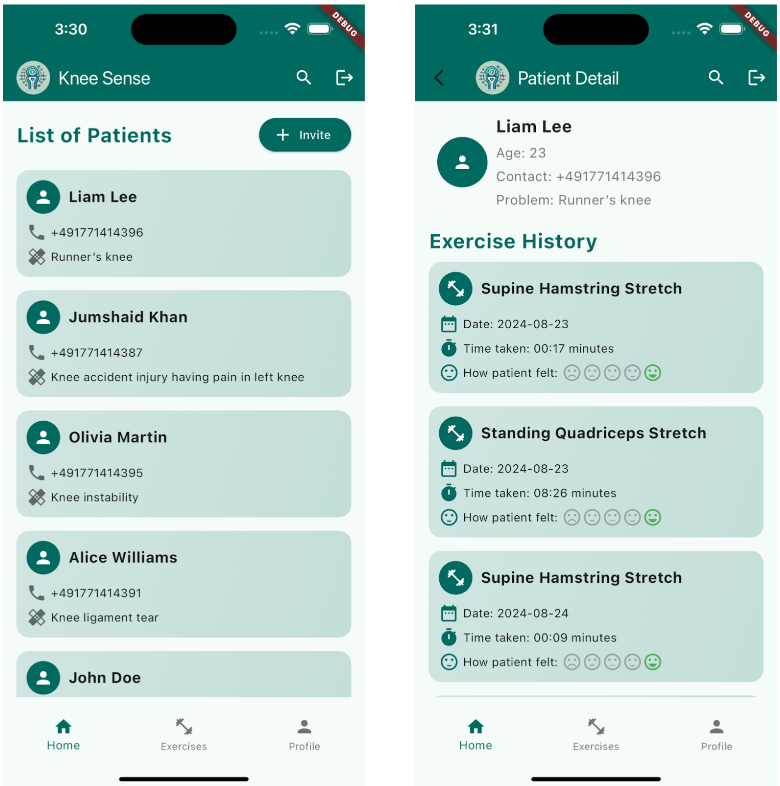
In our mobile application, we have developed a Doctor's end and a patient's end. On Doctor's end, when they log in, they can invite new patients as well as view the existing ones as depicted in Figure 18. They can view personal details of the patients such as their age, contact number, problem/disease, the exercises patients have been performing, how much time it took them and how they felt afterwards. It ensures that Doctors are able to keep track of their patients in a way that is more efficient and saves time.

As shown in Figure 19, Doctors can add new exercises as per requirement of different patients suffering from uncommon injuries or just have a go-to list of exercises. Each exercise can be assigned to any patient and patients on their end can view all the exercises assigned to them by their Doctor. While Doctor is assigning their patient an exercise, they can also add additional comments as shown in Figure. When Doctor adds a new exercise, they can name it, mention the target area of the respective exercise and add instructions - in the form of text, video or images - on how to correctly perform the exercise to maximize benefit.

5.4.2 Patient's end of application

When users log in to KneeSense, they can see the exercises assigned to them by their Doctor as shown in Figure 21 but they can only perform them after they are done with calibrating their orthosis. Once the user wears it correctly, as shown in Figure 21 (b), they are good to go. They are redirected to the home page from where they can start the exercise of their choice.

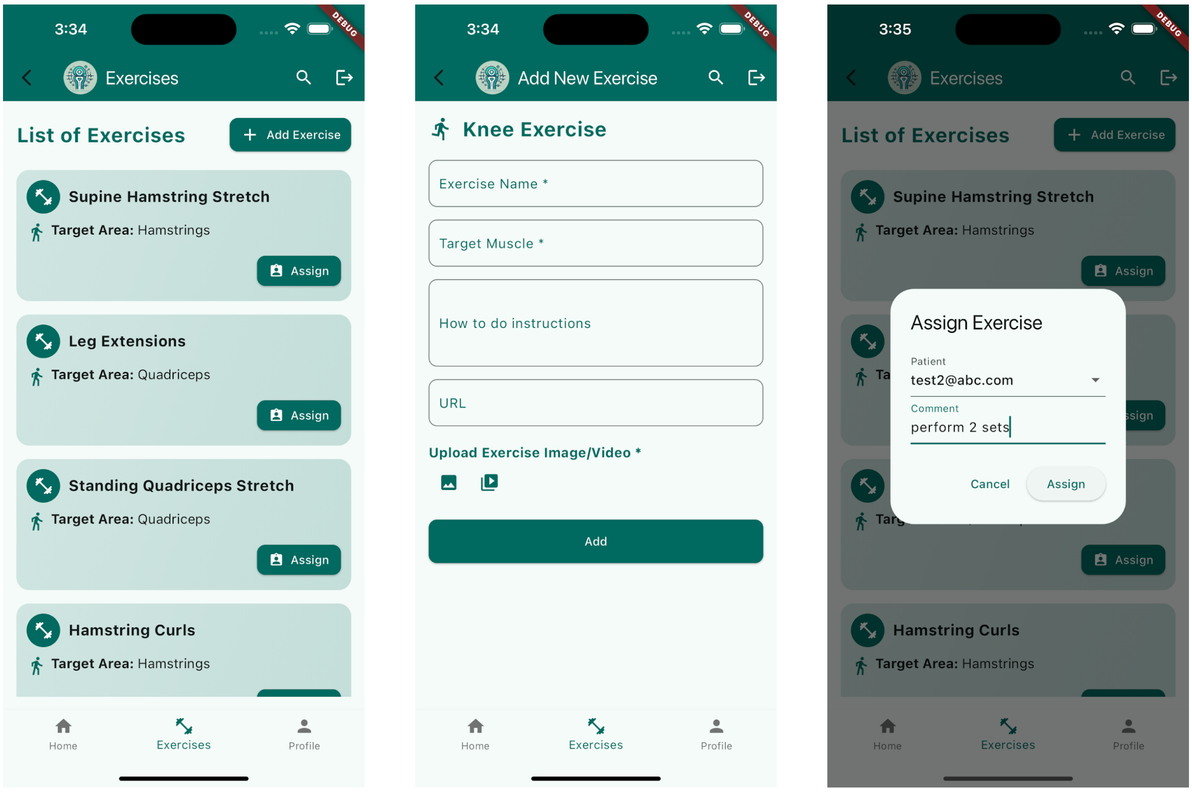
When user starts an exercise, they are redirected to a page that instructs them how to perform the exercise correctly. These instructions are added by their Doctor and can be supported by images/videos or external URLs. When user starts the exercise, they can view the total time it is taking them to perform it, what is the angle of their knees and



(a) (b)

Figure 18: List of patients (a) and details of a patient (b)

what is the temperature of their knee while they are performing the exercise. After user clicks on 'Finish', there comes a popup for feedback from the user to state how they felt, this feedback can be viewed by Doctors. Users can also view their exercises' history, the total time it took, and their feedback regarding that session.



(a) (b) (c)

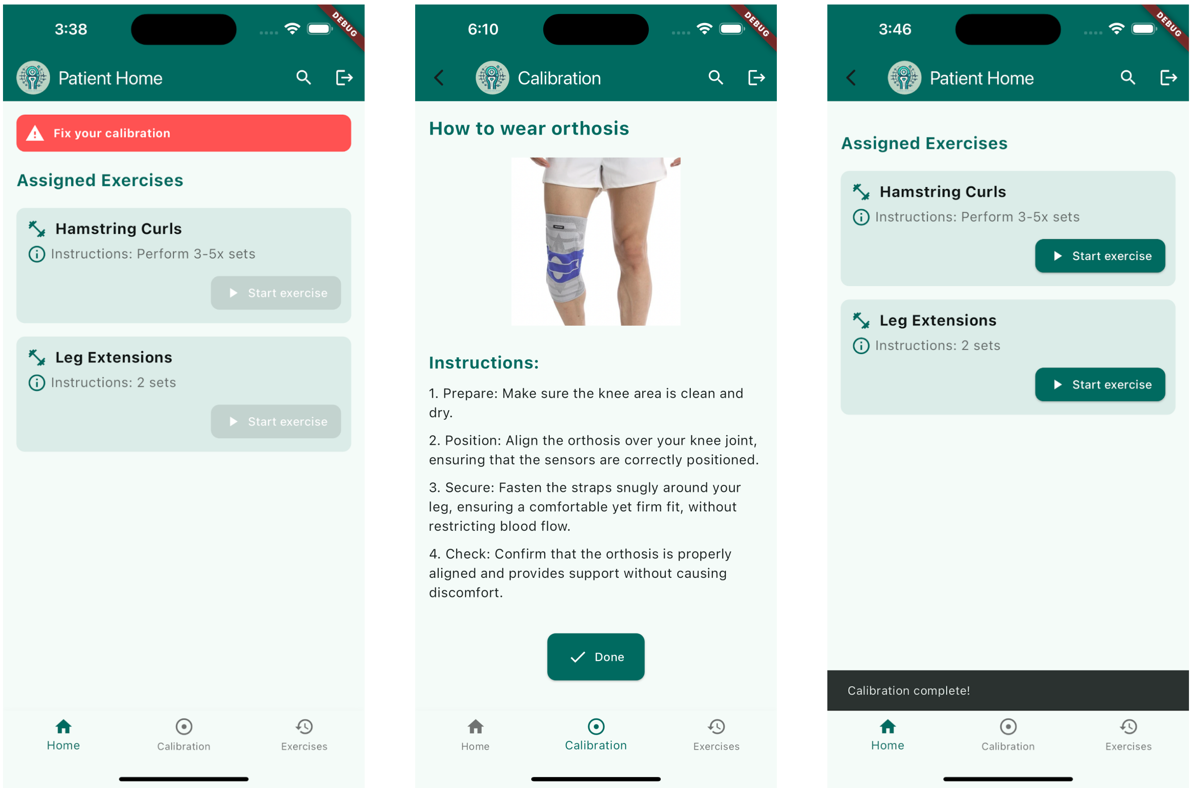
Figure 19: List of exercises on doctor's end (a), doctor assigning exercise to patient(s) (b) and doctor adding new exercise to the list (c)

5.5 Requirements

In this section, we outline the essential hardware and software components required for the development and functionality of our knee orthosis. Table 1 summarizes the key requirements of hardware and software to ensure the orthosis operates smoothly and efficiently.

6 Results

We performed a small study with one participant to test our orthosis. Figure 22 shows the range of the participant's knee angle observed while performing the exercise. 0° knee angle is observed when the patient extends their knee, i.e., both IMUs are in the same plane. The fluctuation in the temperature of the participant's knee can also be seen in the Figure; it is observed that the knee temperature rose as the exercise progressed.



(a) (b) (c)

Figure 20: Home page on patient's end (a), instructions on how to calibrate orthosis (b) and list of exercises assigned to patient (c)

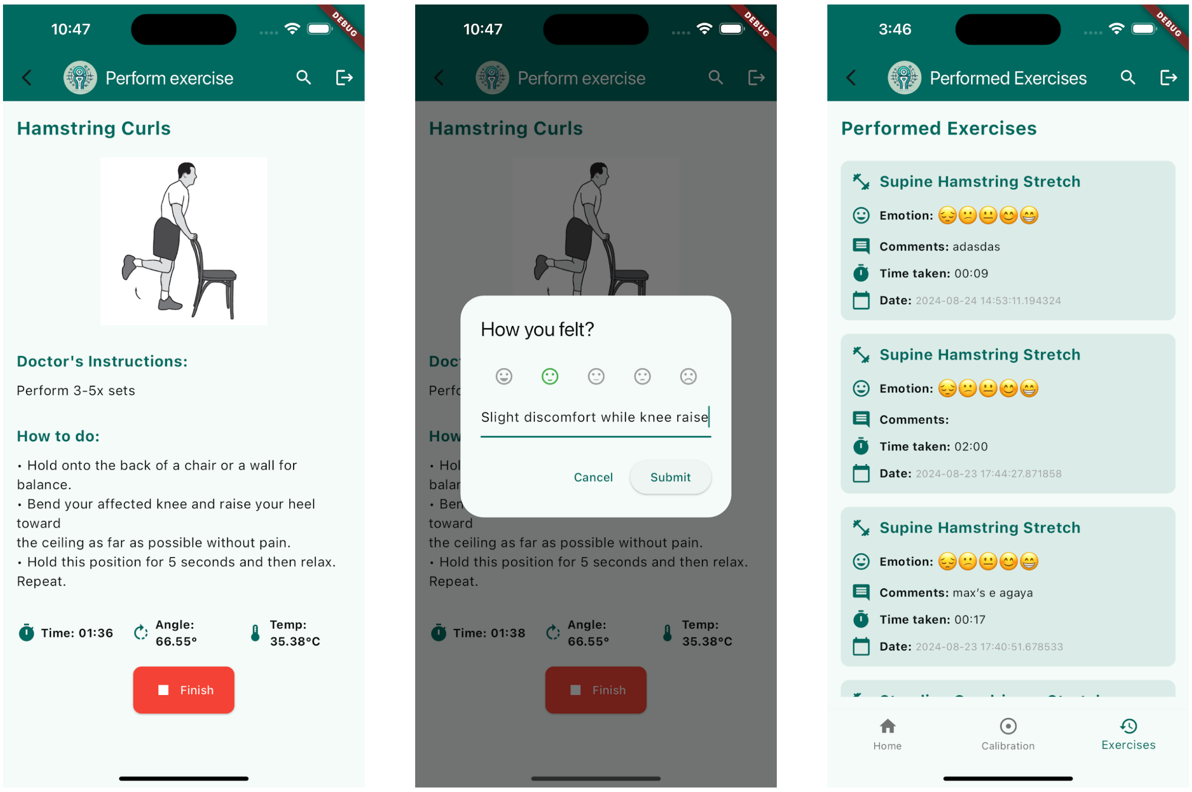
7 Discussion

Our knee orthosis device currently faces several challenges and opportunities for improvement. The reliance on traditional power sources limits its sustainability, and the existing IMU-based knee angle measurement system introduces an offset error, as discussed in Sec. 5, due to the complex knee anatomy. Noise interference in the PCB design affects data reliability, and the current temperature sensors are uncomfortable for prolonged use. Additionally, the need for regular firmware updates could be streamlined with over-the-air capabilities. Addressing these issues will enhance the device's overall functionality and user experience.

8 Future Work

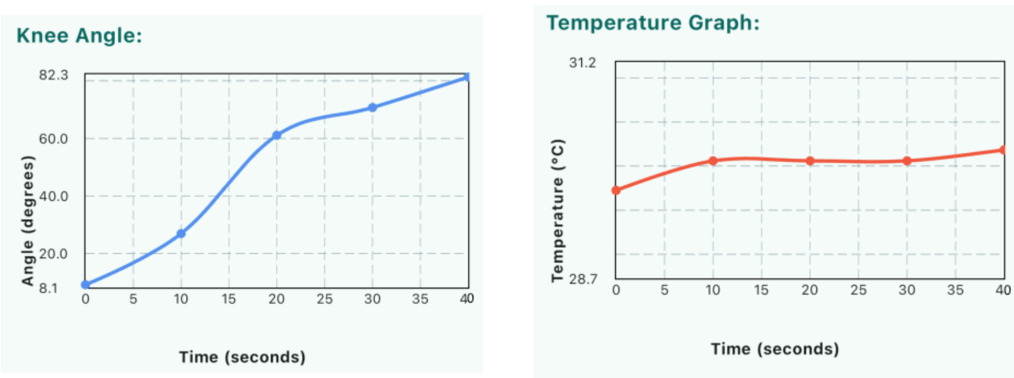
The prototype of the smart knee orthosis has laid a strong foundation, but there are several opportunities for further research and enhancement.

To achieve greater sustainability, we are exploring renewable power sources, such as a knee energy generator that harvests kinetic energy during movement, along with hybrid systems combining energy harvesters with traditional batteries. This will extend operational time and reduce the need for frequent charging.



(a) (b) (c)

Figure 21: Instructions for performing exercise (a), feedback by patient after completing exercise (b) and history of performed exercises (c)



(a) (b)

Figure 22: Knee angle measurement (a) and temperature sensor data (b)

Additionally, we aim to address the issue of offset correction in knee angle measurements caused by the complex knee anatomy. By implementing advanced algorithms, we hope to minimize the current 8-9 degree measurement offset and improve accuracy.

To facilitate maintenance and security, we will incorporate over-the-air (OTA) firmware updates, allowing for seamless software improvements and secure storage of user credentials.

Enhancing the PCB design for noise reduction and signal integrity is another focus, as

Category	Requirements
Hardware Requirements	• Two IMUs: BNO086 • Controllers: ESP32-C3 • Temperature Sensors: DS18B20 • 8 Channel I2c multiplexer • Wires • Battery • Resistor 3 kΩ (for pull up) • Battery driver • Orthosis Knee Support
Software Requirements	• Operating System: iOS 17, Android v14 • Required Software: Flutter v5.2.0, Dart SDK v3.4.4 • Database: firebase_core v3.3.0, firebase_auth v5.1.3

Table 1: Hardware and Software Requirements

a more robust PCB will lead to more reliable data collection. We also plan to improve wearability by replacing bulky temperature sensors with a more flexible matrix embedded in a comfortable, adhesive pad.

We would conduct extensive testing on multiple people who will perform different exercises.

Finally, we would add the feature of progress tracking for patients where they can see how their angle rotation per exercise is improving.

9 Conclusion

Our knee orthosis device advances remote knee monitoring and rehabilitation technology. Integrating sensor-based data collection with a user-friendly mobile application facilitates real-time tracking of knee movements and patient progress, reducing the total time for knee rehabilitation. Despite current limitations related to power supply, measurement accuracy, PCB design, wearability, and data analysis, the device demonstrates substantial potential in improving patient outcomes and optimizing orthopaedic care workflows.

The ongoing efforts to address these challenges will enhance the device's performance and user experience and contribute to more accurate diagnostics and personalized rehabilitation strategies. As we continue to improve the device and address its current challenges, our knee orthosis is set to become a key tool in orthopaedic rehabilitation. It will provide sustainable, reliable, and user-friendly solutions for managing knee health.

References

[1] C. Rehabilitation, "Knee Pain Statistics and Causes - Classic Rehabilitation," https://classicrehabilitation.com/knee-pain-statistics-and-causes/.

[2] P. Sancheti, "Injuries around the knee – Symposium," https://bjsm.bmj.com/content/44/Suppl_1/i1.1, October 11, 2022.

[3] "The next frontier of disruptive parts is coming — uk.eos.info," https://uk.eos.info/en-gb/presscenter/expert-articles/3d-printing-and-smart-sensors.

[4] A. M. GITAU and C. wa MAINA, "Neeflex: A wearable device for measuring knee flexion angles in rehabilitating patients." 2022.

[5] S. I. Lee, J.-F. Daneault, L. Weydert, and P. Bonato, "A novel flexible wearable sensor for estimating joint-angles," in *2016 IEEE 13th International Conference on Wearable and Implantable Body Sensor Networks (BSN)*. IEEE, 2016, pp. 377–382.

[6] D. Rebelo, C. Amma, H. Gamboa, and T. Schultz, "Human activity recognition for an intelligent knee orthosis," in *International Conference on Bio-inspired Systems and Signal Processing*, vol. 2. SCITEPRESS, 2013, pp. 368–371.

[7] P. Félix, J. Figueiredo, C. P. Santos, and J. C. Moreno, "Powered knee orthosis for human gait rehabilitation: First advances," in *2017 IEEE 5th Portuguese Meeting on Bioengineering (ENBENG)*. IEEE, 2017, pp. 1–4.

[8] A. Muro-De-La-Herran, B. Garcia-Zapirain, and A. Mendez-Zorrilla, "Gait analysis methods: An overview of wearable and non-wearable systems, highlighting clinical applications," *Sensors*, vol. 14, no. 2, pp. 3362–3394, 2014.

[9] W.-Y. Lai, H. Ma, W.-H. Liao, D. T.-P. Fong, and K.-M. Chan, "Hip-knee control for gait assistance with powered knee orthosis," in *2013 IEEE international conference on robotics and biomimetics (ROBIO)*. IEEE, 2013, pp. 762–767.

[10] C. Koll, P. Kugler, F. Kluge, S. Reinfelder, U. Jensen, D. Schuldhaus, M. Lochmann, and B. Eskofier, "Estimation of the knee flexion-extension angle during dynamic sport motions using body-worn inertial sensors," 09 2013, pp. 289–295.

[11] T. Seel, J. Raisch, and T. Schauer, "Imu-based joint angle measurement for gait analysis," *Sensors*, vol. 14, no. 4, pp. 6891–6909, 2014.

[12] S. Bakhshi, M. H. Mahoor, and B. S. Davidson, "Development of a body joint angle measurement system using imu sensors," in *2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. IEEE, 2011, pp. 6923–6926.

[13] K. Das, M. BHOWMIK, and D. Mukherjee, "Segmentation of knee thermograms for detecting inflammation," 09 2019, pp. 1550–1554.

[14] P. Majumdar, K. Das, N. Nath, and M. BHOWMIK, "Detection of inflammation from temperature profile using arthritis knee joint datasets," 06 2018, pp. 409–411.

[15] K. Ammer, "Temperature of the human knee - a review," *Thermology International*, vol. 22, pp. 137–151, 10 2012.

[16] Analog Devices, "Ds18b20: Programmable resolution 1-wire digital thermometer," n.d. [Online]. Available: https://www.analog.com/en/products/ds18b20.html#part-details

[17] Melexis, "Mlx90614: Digital plug & play infrared thermometer in to-can," n.d. [Online]. Available: https://www.melexis.com/en/product/MLX90614/Digital-Plug-Play-Infrared-Thermometer-TO-Can

[18] OPUM, "my Digital Knee® - Patient Mobile App — OPUM," https://www.opumtechnologies.com/catalog/digital-knee-gx-7w5wt-8fbzh.

[19] OPED, "Produkte — OPED - Ihr Medizintechnikhersteller aus Bayern," https://oped.de/produkte.

[20] PA Consulting, "Skyre Smart Knee Brace: Reinventing the Patient-Physio Relationship," 2024. [Online]. Available: https://www.paconsulting.com/client-story/skyre-smart-knee-brace-reinventing-the-patient-physio-relationship

[21] Sensoria Health, "Sensoria Smart Knee Brace," 2024. [Online]. Available: https://www.sensoriahealth.com/smart-knee-brace

[22] Dr. Andrew Dutton, "Knee Injuries: Causes, Symptoms, and Treatments," 2024. [Online]. Available: https://www.drandrewdutton.com/blog/knee-injuries/

[23] I. V. Malik, N. Devasenapathy, A. Kumar, H. Dogra, S. Ray, D. Gautam, and R. Malhotra, "Estimation of expenditure and challenges related to rehabilitation after knee arthroplasty: A hospital-based cross-sectional study," *Indian J. Orthop.*, vol. 55, no. 5, pp. 1317–1325, Oct. 2021.

[24] Health Insurance in Germany, "Rehabilitation Benefits in Statutory Health Insurance," 2024. [Online]. Available: https://www.health-insurance.de/statutory-health-insurance/benefits/mandatory/rehabilitation/

[25] Concentra, "Avoid bending to the high cost of knee injuries," n.d. [Online]. Available: https://www.concentra.com/resource-center/articles/avoid-bending-to-the-high-cost-of-knee-injuries/

[26] K. C. Lam, A. N. Marshall, C. E. Welch Bacon, and T. C. Valovich McLeod, "Cost and treatment characteristics of sport-related knee injuries managed by athletic trainers: A report from the athletic training practice-based research network," *Journal of Athletic Training*, vol. 56, no. 8, pp. 922–929, Aug 2021.

[27] A. Dyslin, "Smart knee tech: Remote monitoring," 8 August 2024. [Online]. Available: https://newsnetwork.mayoclinic.org/discussion/smart-knee-technology-allows-care-team-to-remotely-monitor-patients-recovery/

[28] "Global knee braces market size, share & trends analysis report by delivery channel, by product, by application, by regional outlook and forecast, 2024 - 2031," April 2024. [Online]. Available: https://www.kbvresearch.com/knee-braces-market/

[29] Xecor Technologies, "ESP32-C3FN4: Datasheet, Pinout, Features, and Applications," 2024. [Online]. Available: https://www.xecor.com/blog/esp32-c3fn4-datasheet-pinout-features-applications

[30] A. A. of Orthopaedic Surgeon, “Knee Rehabilitation Exercises - OrthoInfo - AAOS,” https://orthoinfo.aaos.org/en/recovery/knee-conditioning-program/knee-pdf/, 2018.

[31] D. Peterson, “Quad Stretch: Tips and Recommended Variations,” https://www.hingehealth.com/resources/articles/quad-stretch/, 28 April 2023.

[32] C.-W. C. Lin, D. Taylor, S. M. Bierma-Zeinstra, and C. G. Maher, “Exercise for osteoarthritis of the knee,” *Physical therapy*, vol. 90, no. 6, pp. 839–842, 2010.

[33] D. Peterson, “Hamstring Curl: Tips and Recommended Variations,” https://www.hingehealth.com/resources/articles/hamstring-curl/, 24 July 2023.

[34] T. Malone, T. A. Blackburn, and L. A. Wallace, “Knee rehabilitation,” *Physical therapy*, vol. 60, no. 12, pp. 1602–1610, 1980.

[35] M. Gemkow, “Leg Extension Muscles Worked, Benefits, & More (Complete Guide),” https://selectfitnessusa.com/blogs/leg-extension-curls/leg-extension-exercise-guide, 14 February 2024.

[36] O. Aoki, N. Tsumura, A. Kimura, S. Okuyama, S. Takikawa, and S. Hirata, “Home stretching exercise is effective for improving knee range of motion and gait in patients with knee osteoarthritis,” *Journal of Physical Therapy Science*, vol. 21, no. 2, pp. 113–119, 2009.

[37] A. Daşkapan, B. KÜLÜNKOĞLU, N. Özünlü Pekyavaş, E. Tüzün, S. Nur Coşar, and M. Karataş, “Comparison of mini-squats and straight leg raises in patients with knee osteoarthritis,” *Turkish Journal of Rheumatology*, vol. 28, no. 1, 2013.

[38] A. I. Faisal, S. Majumder, R. Scott, T. Mondal, D. Cowan, and M. J. Deen, “A simple, low-cost multi-sensor-based smart wearable knee monitoring system,” *IEEE Sensors Journal*, vol. 21, no. 6, pp. 8253–8266, 2021.

[39] M. Fennema, R. Bloomfield, B. Lanting, T. Birmingham, and M. Teeter, “Repeatability of measuring knee flexion angles with wearable inertial sensors,” *The Knee*, vol. 26, no. 1, pp. 97–105, 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0968016018301601

[40] J. Challis, “Quaternions as a solution to determining the angular kinematics of human movement,” *BMC Biomedical Engineering*, vol. 2, 03 2020.

List of Figures

List of Tables