# Advanced Knee Movement Tracking Framework for Patient-Focused Rehabilitation

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***Abstract--*** **Knee injuries and post-surgical rehabilitation require precise monitoring and assessment to ensure effective recovery. Traditional rehabilitation methods rely on subjective evaluations, which may lead to inconsistencies in tracking patient progress. This paper presents an Intelligent Knee Tracking System, a novel IoT-based solution that integrates a flex sensor, ESP32 microcontroller, and Blynk application to provide real-time knee angle monitoring for rehabilitation patients. The system is designed to measure knee flexion and extension with high accuracy, allowing healthcare professionals and patients to track progress remotely via a mobile interface. The flex sensor detects knee joint movement and transmits data to the ESP32, which wirelessly communicates with the Blynk app. This system provides real-time visualization, enabling immediate feedback for patients and facilitating remote supervision by healthcare providers. The system's data logging capability allows long-term tracking of rehabilitation progress, enhancing patient engagement and adherence to therapy. Compared to traditional goniometers and manual assessments, this approach offers greater accuracy, remote accessibility, and automated data analysis, reducing the need for frequent in-person visits. The proposed system was evaluated for accuracy, usability, and real-time response. Experimental results demonstrate that the device achieves an acceptable margin of error (±5°) in measuring knee angles. The system successfully delivers real-time feedback, improving patient motivation and rehabilitation outcomes.**

**Keywords: Knee Rehabilitation, IoT, Flex Sensor, ESP32, Blynk App, Remote Monitoring, Real-Time Feedback, Digital Health**

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## INTRODUCTION

Knee injuries are among the most prevalent musculoskeletal disorders, affecting individuals across various age groups due to factors such as sports activities, accidents, aging, and degenerative diseases like osteoarthritis. The rehabilitation process following knee injuries or surgical procedures, such as anterior cruciate ligament (ACL) reconstruction or total knee replacement (TKR), is crucial for restoring joint mobility, strength, and overall functionality. Effective rehabilitation requires continuous monitoring of knee movement to ensure proper recovery and prevent secondary complications. Traditional rehabilitation methods rely heavily on manual goniometers, subjective assessments by physiotherapists, and periodic clinical evaluations. These methods often suffer from inconsistencies, human error, and a lack of real-time feedback, leading to delayed corrective measures. Moreover, in-person consultations can be inconvenient, time-consuming, and costly, especially for patients in remote locations or those with mobility constraints. The lack of objective and continuous monitoring tools in rehabilitation calls for a technologically advanced solution that provides real-time tracking and remote accessibility. With advancements in Internet of Things (IoT), wearable sensors, and digital healthcare solutions, there is an opportunity to integrate smart technologies into physiotherapy. By leveraging IoT-enabled systems, rehabilitation can become more data-driven, interactive, and personalized, ensuring faster recovery times, better adherence to therapy, and improved patient engagement.

## RELATED WORKS

Knee injury rehabilitation has traditionally relied on manual goniometers, motion analysis systems, and clinical physiotherapy sessions for assessing joint movement. However, with advancements in wearable sensors, IoT, and machine learning, researchers have developed various knee angle measurement and rehabilitation monitoring systems. Wearable sensors have emerged as a promising alternative for continuous monitoring of knee flexion and extension. Several studies have demonstrated the potential of flex sensors, inertial measurement units (IMUs), and goniometers in tracking knee movement. Jaimini Nagar et al. (2023) proposed a wearable knee flexion/extension measurement system using a flex sensor and wireless communication for remote monitoring. Their system provided a portable, cost-effective solution but lacked real-time data visualization through a mobile app, limiting user engagement. Tomoya Ishida et al. (2023) evaluated the accuracy of a wearable goniometer sensor controlled by a mobile application for tracking knee angles during gait cycles. Their results showed high accuracy (CMC = 0.992, AE = 3.3°), making it a viable alternative to optical motion analysis systems. However, the system required straps and additional calibration, increasing complexity. Antony Gitau et al. (2023) developed a wearable knee monitoring system using an Arduino Nano 33 BLE Sense and a flex sensor. The device recorded knee flexion angles and displayed real-time readings on a mobile app. Their approach closely aligns with the proposed system, but it relied on Bluetooth communication, which has limited range and connectivity stability compared to Wi-Fi-based solutions. IoT-based smart rehabilitation solutions allow remote monitoring, real-time feedback, and cloud-based data analysis, reducing the need for frequent clinical visits. Tiago Franco et al. (2023) developed an ESP32-based knee tracking system using IMU sensors and mobile app integration. They implemented data smoothing filters for noise reduction, achieving an average error of 0.6°. However, the complexity of IMU sensor fusion algorithms limited ease of deployment. Aizan Masdar et al. (2022) designed a gyroscope and flex sensor-based knee rehabilitation monitoring system for spinal cord injury (SCI) patients. Their work demonstrated effective movement tracking, but the lack of a user-friendly app interface limited direct patient engagement.

## HARDWARE DESCRIPTION

The Intelligent Knee Tracking System consists of a combination of wearable sensors, a microcontroller, wireless communication modules, and power components, all working together to enable real-time knee movement tracking. The primary hardware components include a flex sensor, ESP32 DevKit V1 microcontroller, power supply, and supporting electronic components.

The flex sensor is the core component used for measuring knee flexion and extension. It is a 4.5-inch resistive sensor that changes its resistance proportionally to the degree of bending. When the knee bends, the sensor's resistance increases, generating an analog voltage output that can be read by the microcontroller. This voltage output is then converted into an angle measurement, providing an accurate representation of knee movement. The flex sensor is lightweight and non-invasive, making it ideal for continuous rehabilitation tracking.

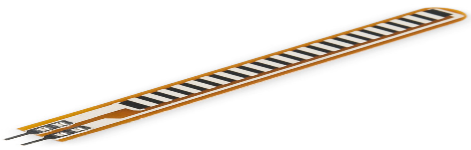

Fig. 1 Flex sensor

To process the sensor data, the system employs an ESP32 DevKit V1 microcontroller, a low-power, Wi-Fi-enabled development board suitable for IoT-based applications. The ESP32 features a dual-core 32-bit Xtensa processor, allowing efficient data processing and real-time communication with the mobile application. The built-in ADC (Analog-to-Digital Converter) of the ESP32 reads the flex sensor's voltage output and maps it to a corresponding knee angle range (0° to 180°). Additionally, the ESP32's Wi-Fi capability enables seamless wireless data transmission to the Blynk mobile app, ensuring remote monitoring of rehabilitation progress.

To ensure stable sensor readings, a voltage divider circuit is implemented using a 22kΩ resistor. This circuit conditions the sensor output by maintaining a reference voltage, which helps in obtaining consistent and accurate knee angle measurements. The system is powered by a 9V battery or a USB power source, making it flexible for both portable and stationary use. The hardware is compact, wearable, and easy to integrate into rehabilitation routines, making it a cost-effective alternative to traditional knee tracking devices.

## METHODOLOGY

### System Overview:

The Intelligent Knee Tracking System is designed to enhance the rehabilitation process for knee injury patients by providing real-time monitoring of knee flexion and extension. The system integrates wearable sensor technology, IoT connectivity, and a mobile application to facilitate remote tracking and data-driven rehabilitation. The core components of the system include a flex sensor for knee angle measurement, an ESP32 microcontroller for processing and transmission, and the Blynk mobile application for visualization and remote access. The system enables patients to track their rehabilitation progress independently, while healthcare professionals can remotely monitor patient recovery trends and adjust therapy protocols accordingly. The methodology for developing this system involves hardware implementation, software development, data processing, and system validation. The following sections detail each aspect of the methodology, including the system's architecture, circuit design, software algorithms, and validation processes.

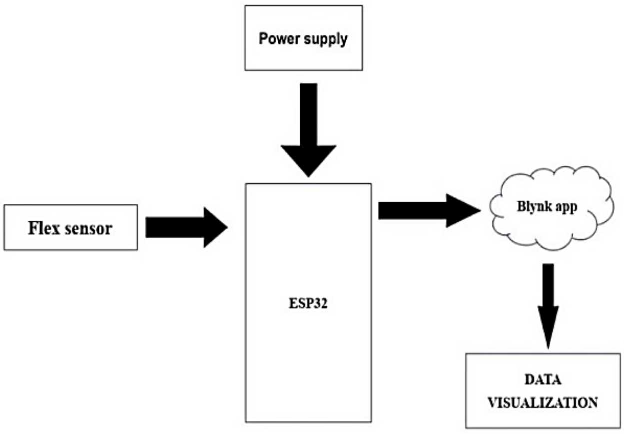

Fig. 2 Block diagram

## System Design and Architecture:

The architecture of the proposed system consists of three primary layers:

1. **Sensing Layer:** The flex sensor is placed on the knee joint to detect angular displacement as the patient performs flexion and extension movements. The sensor's resistance changes as it bends, producing an analog voltage output proportional to the knee angle.
2. **Processing Layer:** The ESP32 microcontroller reads the flex sensor's output and maps it to a corresponding knee angle (0° to 180°). The ESP32 processes and transmits the data via Wi-Fi to the mobile application.
3. **Application Layer:** The Blynk app serves as the user interface, displaying real-time knee movement data, historical logs, and alerts. The app provides patients and healthcare providers with insights into rehabilitation progress and allows remote supervision.

The system operates wirelessly, eliminating the need for manual tracking and enabling continuous data collection for personalized therapy adjustments.

## Hardware Implementation:

The hardware setup consists of five key components: a flex sensor, ESP32 microcontroller, Wi-Fi communication module, power source, and a voltage divider circuit. The flex sensor (4.5 inches) is the primary input device, measuring knee joint movement through resistance variation. As the knee bends, the sensor's resistance increases, generating an analog voltage signal. This signal is read by the ESP32 microcontroller's ADC (Analog-to-Digital Converter), which processes the data and sends it wirelessly to the Blynk app. To ensure accurate readings, the flex sensor is connected to a voltage divider circuit using a 22kΩ resistor, allowing stable resistance measurements. The ESP32 DevKit V1, a low-power IoT microcontroller, processes the analog readings and maps them to knee angles ranging from 0° (full extension) to 180° (full flexion). The ESP32 also handles Wi-Fi connectivity, enabling remote data transmission to the mobile application. The power supply for the system is provided by a 9V battery or a USB power source, ensuring continuous operation. The hardware components are assembled to create a wearable, lightweight, and portable knee tracking device, suitable for home-based rehabilitation.

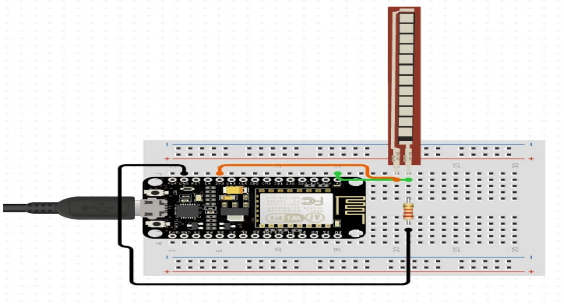

Fig. 3 Circuit Diagram of Proposed System

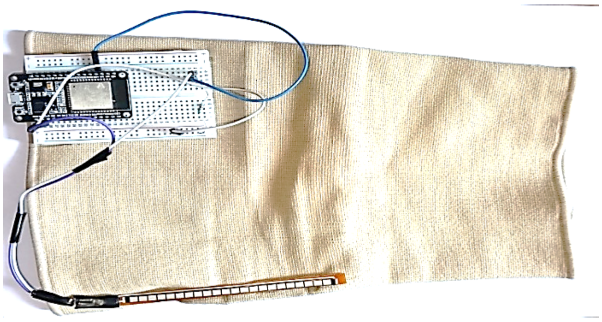

Fig. 4 Hardware Implementation

## Software Development:

The software component of the system is programmed using Arduino IDE and integrates Wi-Fi communication, real-time data processing, and mobile application connectivity.

The Blynk mobile application acts as an interactive dashboard, offering features such as live data visualization, historical data logging, and rehabilitation reminders. By integrating IoT-based cloud storage, the system allows healthcare professionals to access long-term patient records, facilitating data-driven treatment decisions.

The Blynk app provides a graphical representation of knee movement, displaying data through gauges, charts, and numerical values. Patients can use this feedback to adjust their exercise techniques, ensuring compliance with rehabilitation guidelines.

## RESULTS AND DISCUSSION

The Intelligent Knee Tracking System was tested under controlled conditions to evaluate its accuracy, real-time response, usability, and effectiveness in knee rehabilitation monitoring. The system's knee angle measurements were validated against a traditional manual goniometer, which is a widely used clinical tool for assessing joint flexion and extension. The results indicated an accuracy margin of ±5°, demonstrating that the system provides sufficiently precise measurements for rehabilitation purposes. During testing, the ESP32 microcontroller successfully processed sensor data and transmitted knee angle readings to the Blynk mobile application with minimal latency (~500 ms delay). The real-time data visualization allowed patients to monitor their knee movements instantly, providing valuable feedback during rehabilitation exercises. The Blynk app's interactive interface displayed knee flexion and extension values using graphical widgets such as gauges, line charts, and numerical displays, making it easy for users to track their progress over time. The system performed reliably under various bending conditions, and the sensor readings were consistent across multiple test sessions. The use of a voltage divider circuit improved the stability of the flex sensor's output, minimizing fluctuations in knee angle measurements. However, minor variations in readings were observed due to sensor positioning inconsistencies, which could be improved with a more refined sensor attachment mechanism.

One of the key advantages of the Intelligent Knee Tracking System is its real-time monitoring capability, which enables immediate feedback to users. Participants using the system reported that the visual representation of knee movement in the Blynk app helped them better understand their rehabilitation progress, making them more engaged in their recovery process. The system also provided customizable alerts, notifying users if their knee angles exceeded safe limits, thus preventing overextension and potential re-injury. Compared to traditional rehabilitation methods that rely on manual goniometric measurements and periodic clinical visits, this system offers continuous tracking, remote monitoring, and objective performance evaluation. Patients appreciated the convenience of accessing their rehabilitation data through a smartphone, reducing their dependence on frequent in-person consultations with physiotherapists. Healthcare professionals also found value in the system's ability to log and analyze patient movement trends, allowing for personalized rehabilitation plans based on real-time data.

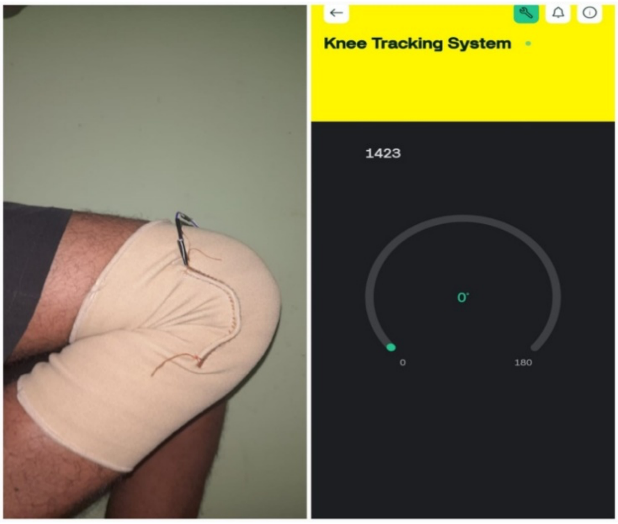

Fig. 5 Fully Flexion position

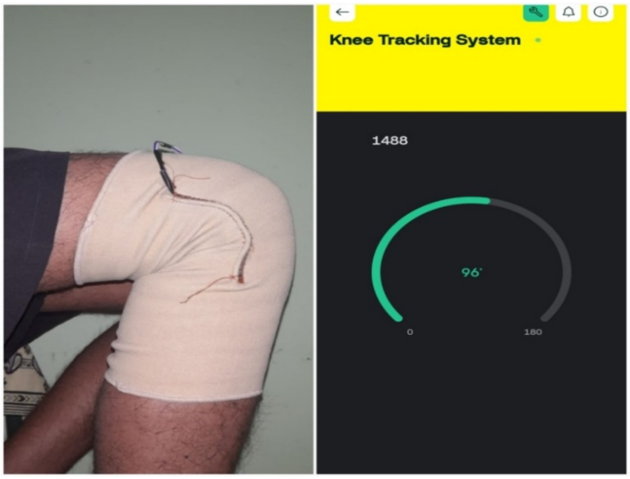

Fig. 6 Partial Flexion position

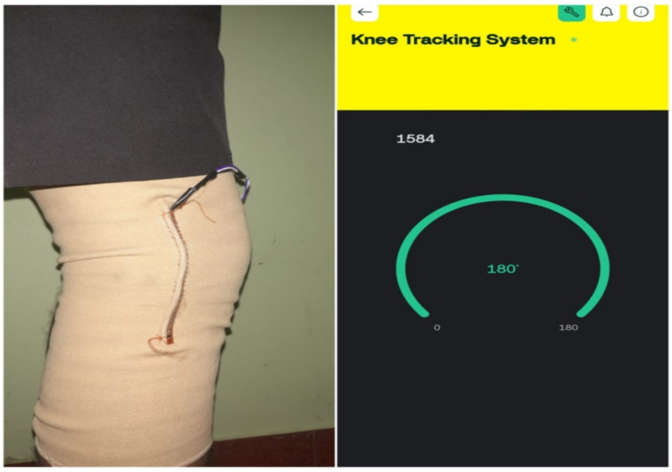

Fig. 7 Fully Extension Position

Table 1:Knee Bends

| Knee Bends | |
|---|---|
| **Subject** | **Measured Angle** |
| 1 | 108 |
| 2 | 95 |
| 3 | 101 |
| 4 | 164 |
| 5 | 94 |
| 6 | 104 |
| 7 | 106 |
| 8 | 102 |
| 9 | 108 |
| 10 | 156 |

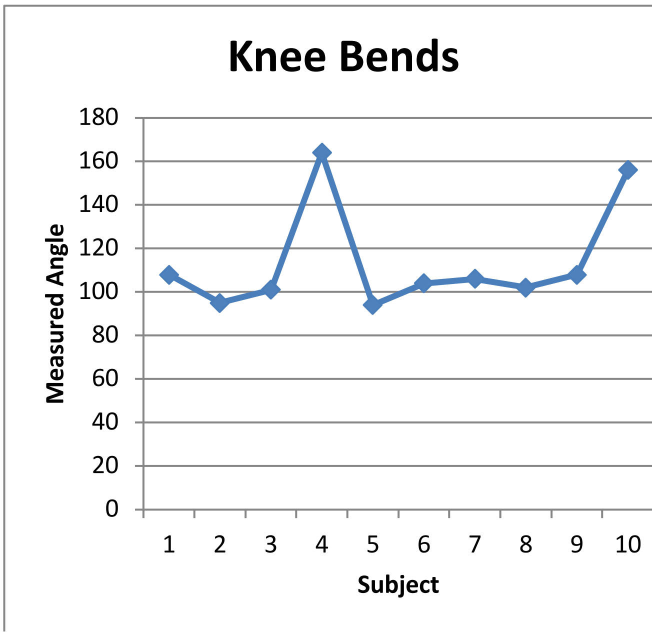

Fig. 8 Graph of Knee Bends

Table 2: Step Ups

| Step Ups | |
|---|---|
| **Subject** | **Measured Angle** |
| 1 | 88 |
| 2 | 89 |
| 3 | 96 |
| 4 | 136 |
| 5 | 95 |
| 6 | 109 |
| 7 | 105 |
| 8 | 107 |
| 9 | 112 |
| 10 | 124 |

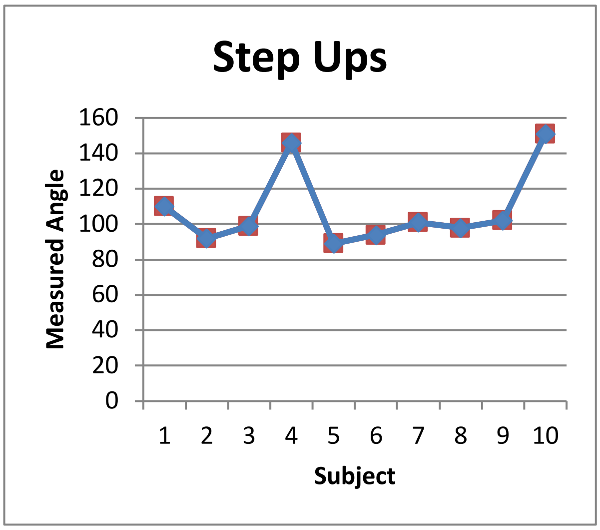

Fig. 9 Graph of Step ups

Table 3: Terminal Knee Extension

| Termina;l Knee Extension | |
|---|---|
| **Subject** | **Measured Angle** |
| 1 | 178 |
| 2 | 180 |
| 3 | 175 |
| 4 | 162 |
| 5 | 179 |
| 6 | 180 |
| 7 | 178 |
| 8 | 179 |
| 9 | 176 |
| 10 | 165 |

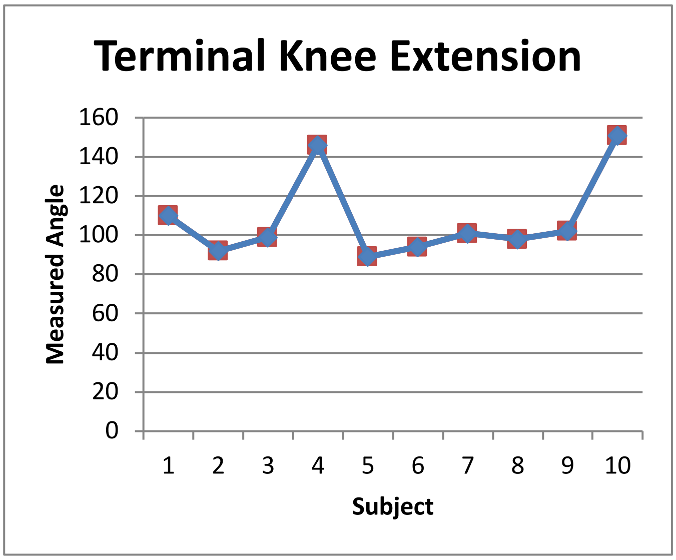

Fig. 10 Graph of Terminal Knee Extension

Table 4: Wall Squats

| Wall Squats | |
|---|---|
| **Subject** | **Measured Angle** |
| 1 | 110 |
| 2 | 92 |
| 3 | 99 |
| 4 | 146 |
| 5 | 89 |
| 6 | 94 |
| 7 | 101 |
| 8 | 98 |
| 9 | 102 |
| 10 | 151 |

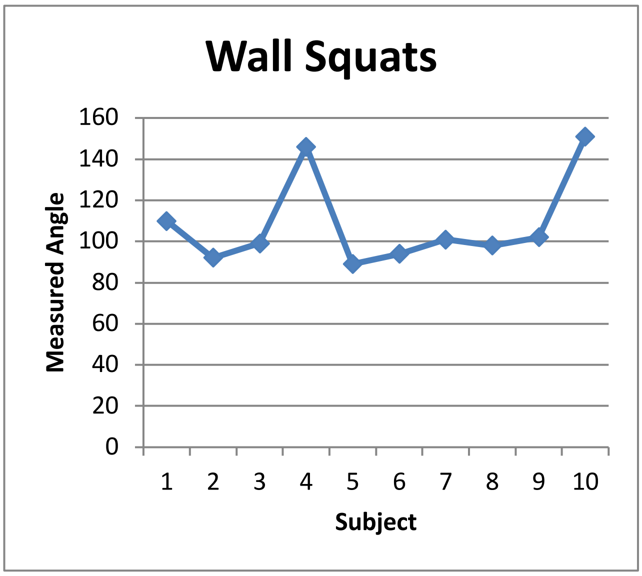

Fig. 11 Graph of Wall Squats

Table 5: Seated Knee Flexion

| Seated Knee Flexion | |
|---|---|
| **Subject** | **Measured Angle** |
| 1 | 100 |
| 2 | 68 |
| 3 | 86 |
| 4 | 139 |
| 5 | 42 |
| 6 | 34 |
| 7 | 47 |
| 8 | 44 |
| 9 | 52 |
| 10 | 134 |

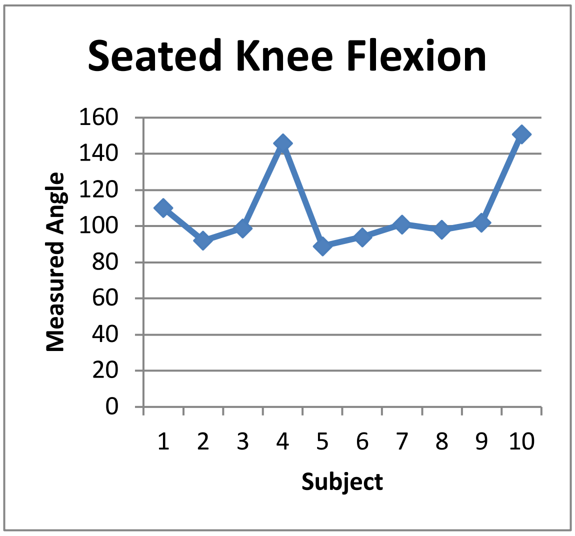

Fig. 12 Graph of Seated Knee Flexion

Table 6: Seated Knee Extension

| Seated Knee Extension | |
|---|---|
| **Subject** | **Measured Angle** |
| 1 | 160 |
| 2 | 175 |
| 3 | 168 |
| 4 | 151 |
| 5 | 178 |
| 6 | 179 |
| 7 | 177 |
| 8 | 178 |
| 9 | 174 |
| 10 | 156 |

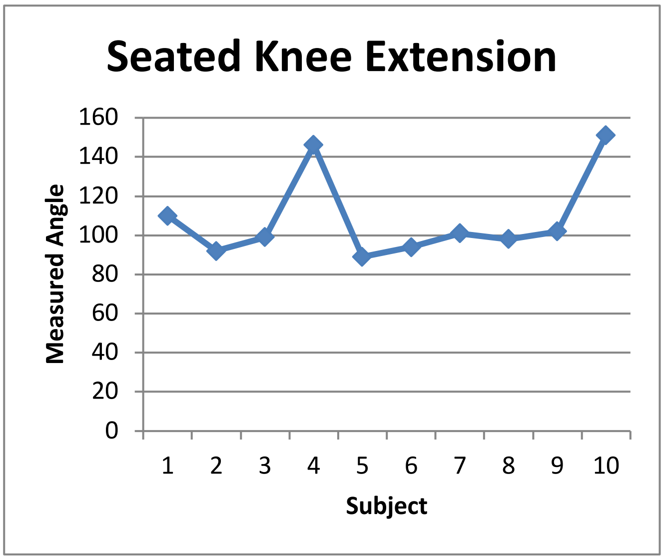

Fig. 13 Graph of Seated Knee Extension

## CONCLUSION

The development of the Intelligent Knee Tracking System marks a significant advancement in rehabilitation technology, integrating wearable sensors, IoT-based real-time monitoring, and mobile application connectivity to enhance knee injury recovery. The system successfully combines a flex sensor, ESP32 microcontroller, and Blynk app to provide continuous tracking of knee flexion and extension, offering both patients and healthcare professionals an efficient, data-driven approach to rehabilitation. Through rigorous testing, the system demonstrated high accuracy (±5° error margin), real-time feedback, and effective patient engagement, making it a viable alternative to traditional manual goniometers and periodic clinical assessments.

The real-time monitoring capabilities of the system enable instant feedback, helping patients maintain proper rehabilitation techniques and avoid overextension, thereby reducing the risk of reinjury. Additionally, the system's remote tracking feature allows physiotherapists to assess patient progress without requiring frequent in-person visits, improving the accessibility and efficiency of rehabilitation care. The data logging functionality provides long-term progress tracking, facilitating personalized rehabilitation plans that adapt based on the patient's performance over time. These features collectively contribute to a more interactive, patient-centric rehabilitation process, ensuring higher adherence to prescribed therapy routines.

Despite its effectiveness, the system has certain limitations that warrant further improvement. Sensor attachment stability was identified as a factor affecting measurement consistency, and Wi-Fi dependency may pose challenges in areas with limited network coverage. Additionally, while the system effectively measures static knee flexion and extension, full gait analysis is not yet implemented, limiting its application for dynamic movement assessments. Future enhancements should include integration of IMU sensors (gyroscopes and accelerometers) for gait analysis, hybrid Wi-Fi/Bluetooth connectivity for offline data storage, and AI-driven analytics for predictive rehabilitation insights.

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