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Wearable Knee Support Sensor for Real-Time Knee Flexion Monitoring

Ayffa Eriqha Rajali[1], Muhammad Rusydi Muhammad Razif[1*], Nurul Hasyimah Mohd Mustapha[1], Ili Najaa Aimi Mohd Nordin[1], Muhammad Ammar Hafidz Mohamed Azly[1]

[1] *Department of Electrical Engineering Technology, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, 84600 Pagoh, Johor, MALAYSIA*

*Corresponding Author: rusydi@uthm.edu.my
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Abstract

Wearable rehabilitation technologies are increasingly adopted in clinical and home-based settings. These technologies support continuous and objective monitoring of joint movement during the recovery process. This project presents the development of a wearable knee support sensor system for real-time knee flexion monitoring in rehabilitation applications. A flexible resistive sensor fabricated using conductive threads composed of polyester, silver, and stainless-steel fibres embedded within a flexible rubber substrate is integrated into a knee support to detect knee bending through resistance variation. An ESP32-S3 microcontroller acquires the sensor data and transmits the measurements wirelessly to a cloud based ThingsBoard dashboard for real-time visualization and analysis. Experimental results demonstrate a strong and consistent correlation between knee flexion angle and resistance values, confirming stable and repeatable sensor performance. Based on predefined resistance thresholds, the system automatically classifies knee condition into normal movement, moderate stiffness, or conditions requiring physiotherapy attention, which are displayed on the dashboard in real time. The classification results demonstrated consistent and accurate condition identification during experimental testing, indicating the effectiveness of the threshold-based assessment approach for rehabilitation monitoring. The experiment indicate that the developed system provides reliable knee flexion measurement, reduces reliance on manual assessment, and offers a practical solution for both clinical and home-based knee rehabilitation monitoring.

1. Introduction

Rehabilitation is a critical process in restoring functional movement, mobility, and quality of life for individuals affected by injury, surgery, or musculoskeletal disorders*(Clark, 2025)(Wei et al., 2025)*. The growing demand for rehabilitation services, driven by aging populations and increased incidence of knee-related conditions, has placed greater emphasis on accurate and continuous assessment methods *(Yasser & Solayman, 2024*). Knee rehabilitation requires precise monitoring of joint movement to evaluate recovery progress, guide therapy adjustments, and prevent secondary injuries(*Zhu et al., 2024)(Shetty et al., 2025)*. However, conventional rehabilitation practices continue to rely heavily on manual assessment techniques, such as visual observation and goniometric measurements, which are limited by subjectivity, inter-observer variability, and the inability to capture dynamic knee movement during daily activities.

Advanced measurement techniques have been introduced to improve knee motion assessment accuracy. Radio Stereometric Analysis (RSA) (Nagarajapandian *et al.*, 2023) has demonstrated high precision by tracking knee motion across multiple planes from a defined reference position, while parameters such as Q-angle, range of motion (ROM) *(Singh et al., 2024),* muscle strength, and functional performance are commonly used as outcome measures following procedures such as total knee arthroplasty. Rehabilitation protocols are typically structured into progressive phases, including early-stage pain management, Continuous Passive Motion (CPM) *(Singh et al., 2024)*, range of motion exercises, strength training, gait rehabilitation, and later-stage functional and proprioceptive training. Although these approaches are effective, existing measurement methods remain impractical for continuous, real-time, and home-based monitoring due to their complexity, cost, and reliance on clinical environments.

Recent advances in wearable sensing technologies have provided alternative solutions for knee rehabilitation monitoring. Flexible sensors have gained attention for their ability to bend, stretch, and conform to human joint movement while safely interacting with the body *(Kabir et al., 2024)*. These sensors convert mechanical deformation into electrical signals such as resistance, capacitance, voltage, or current, enabling quantitative measurement of knee bending *(Baek and Park, 2024)(Suzumori and Nabae, 2025).* Studies have shown that resistance-based flexible sensors, particularly those fabricated using conductive materials, exhibit a proportional relationship between resistance variation and knee flexion *angle (Wang et al., 2022)(Gu et al., 2023)*. Developments in material science have further enhanced sensor performance using stretchable conductive threads, thin-film sensors, capacitive strain sensors, soft robotic structures, and three-dimensional printed conductive materials. Conductive thread–based sensors embedded or sewn into flexible substrates have demonstrated advantages in wearability, durability, and suitability for repeated knee motion compared to rigid or optical sensing systems *(Mustapha et al., 2023*)*.*

The integration of Internet of Things (IoT) technology has further transformed rehabilitation monitoring by enabling wireless data transmission, centralized data storage, and remote accessibility (Nagarajapandian *et al.*, *2023).* IoT-based rehabilitation systems commonly utilise microcontrollers with built-in wireless communication, such as ESP32 platforms *(Singh et al. 2024)*, combined with motion, force, or flex sensors to replace manual assessment with automated, real-time monitoring. In related studies, IoT solutions have been applied in hospital, intensive care unit (ICU), and home-care settings, particularly for elderly patients requiring continuous supervision. Advanced analytical techniques, including Long Short-Term Memory (LSTM), Decision Trees, and Artificial Neural Networks (ANN), have been employed to analyse physiological and movement data, improving predictive capability and supporting data-driven rehabilitation decisions *(Qin et al., 2024)*.

Equally important in IoT-based rehabilitation systems is the use of software dashboards for data visualization and interpretation. Early systems frequently relied on platforms such as LabVIEW for real-time data acquisition and visualization *(R.Kalaivani et al., 2025)(Forsyth et al., 2024)*. However, these solutions often required complex configuration and local deployment. More recent studies have demonstrated the effectiveness of cloud-based dashboards such as ThingsBoard, which support real-time data streaming, historical data logging, and customizable visualization through widgets such as time-series graphs and numerical indicators *(Mafop, Abidin and Mohamad, 2024)*. The built-in rule engine in ThingsBoard enables automated threshold-based alerts without the need for additional software development, improving system responsiveness while reducing overall complexity. Real-time dashboard feedback has been shown to enhance patient engagement, support adherence to rehabilitation programs, and enable timely intervention by healthcare professionals *(Dwiyaniti et al., 2023)*.

Based on these developments, this paper presents a wearable knee flexion monitoring system that integrates a flexible resistive sensor fabricated using conductive thread embedded within a flexible rubber substrate, an ESP32-S3 microcontroller for data acquisition and wireless transmission, and a cloud-based ThingsBoard dashboard for real-time visualization and knee condition assessment. The proposed system aims to address the limitations of conventional rehabilitation assessment by providing continuous, objective, and accessible knee flexion monitoring suitable for both clinical and home-based rehabilitation environments.

2. Methodology

The system block diagram in Figure 1 shows the overall architecture of the wearable knee flexion monitoring system. The process begins with a flexible resistive sensor integrated into a knee support, which detects resistance changes during knee flexion. These signals are acquired and processed by an ESP32-S3 microcontroller, which converts the analogue sensor data into digital form. The processed data transmitted wirelessly to a cloud-based server and visualized in real time through a ThingsBoard dashboard, enabling continuous monitoring and assessment of knee movement during rehabilitation.

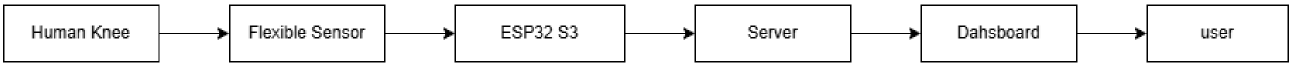

Fig 1 *System block diagram*

The project algorithm in Figure 2 was designed to enable continuous and real-time monitoring of knee flexion using a wearable sensing system integrated with an IoT platform. The algorithm begins with the initialization of the ESP32-S3 microcontroller, including the configuration of analogue input channels, wireless communication parameters, and cloud connection settings. Once initialized, the system enters a continuous monitoring loop where resistance values from the flexible sensor are sampled through the analogue-to-digital converter. These readings correspond to mechanical deformation of the conductive thread caused by knee flexion and extension.

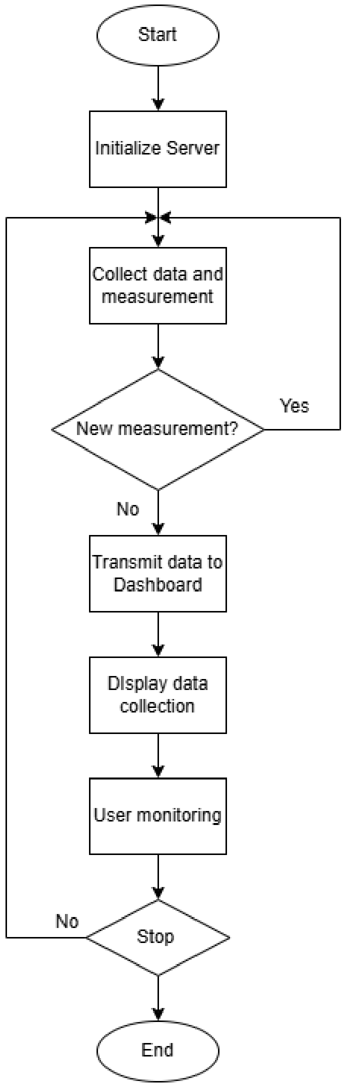

Fig 2 *Project Algorithm for ESP32-S3*

The acquired analogue signals are processed to obtain resistance values, which are then mapped to knee flexion behaviour based on predefined calibration and threshold ranges. The processed data are packaged into telemetry messages and transmitted wirelessly to the cloud server using a lightweight communication protocol. Upon successful transmission, the system waits for the next sampling interval before repeating the measurement cycle. This continuous loop enables real-time acquisition, processing, and transmission of knee flexion data. The algorithm also includes basic validation to ensure stable readings before transmission, improving data reliability for visualization and analysis on the monitoring dashboard.

The flexible sensor was first designed using AutoCAD in Figure 3 (a) to define the geometry, dimensions, and structural layout prior to fabrication. The AutoCAD model illustrates a rectangular sensor profile with a recessed channel pattern arranged along the sensing region, which was intended to guide the placement of the conductive thread and ensure uniform strain distribution during bending. This patterned design helps maintain consistent deformation of the sensing element when the knee undergoes flexion, thereby improving measurement stability and repeatability. The overall dimensions and thickness were selected to balance flexibility and mechanical support, ensuring that the sensor could conform naturally to knee movement without causing discomfort to the user.

Following the design stage in Figure 3 (b), the sensor was fabricated on a flexible silicone rubber substrate based on the AutoCAD layout. Conductive thread composed of polyester, silver, and stainless-steel fibres was embedded within the silicone structure according to the predefined channel pattern. The silicone rubber in provided elasticity, durability, and electrical insulation, while the conductive thread functioned as the resistive sensing element. Electrical terminals were extended from both ends of the conductive thread to allow connection to the measurement circuit. The fabricated sensor closely matched the AutoCAD design, demonstrating the effectiveness of the digital modelling approach in translating the design into a physical prototype. This combination of CAD-based design and flexible material fabrication ensured consistent sensor performance and suitability for integration into a wearable knee support for rehabilitation monitoring.

(a) (b)

Fig 3 *Flexible sensor design using AutoCAD (a) and fabrication on flexible rubber (b)*

The experimental setup in Figure 4 consisted of a flexible resistive sensor integrated into a wearable knee support and connected to an ESP32-S3 microcontroller for data acquisition. The conductive thread–based sensor was positioned along the knee joint to ensure consistent deformation during knee flexion and extension. The sensor output was connected to the ESP32-S3 through a voltage divider circuit to measure resistance changes accurately. During testing, the microcontroller was powered externally and configured to transmit sensor data wirelessly to a cloud-based ThingsBoard platform. The dashboard displayed real-time resistance values, knee flexion behavior, and knee condition indicators, enabling continuous monitoring and evaluation of knee movement during the experiment.

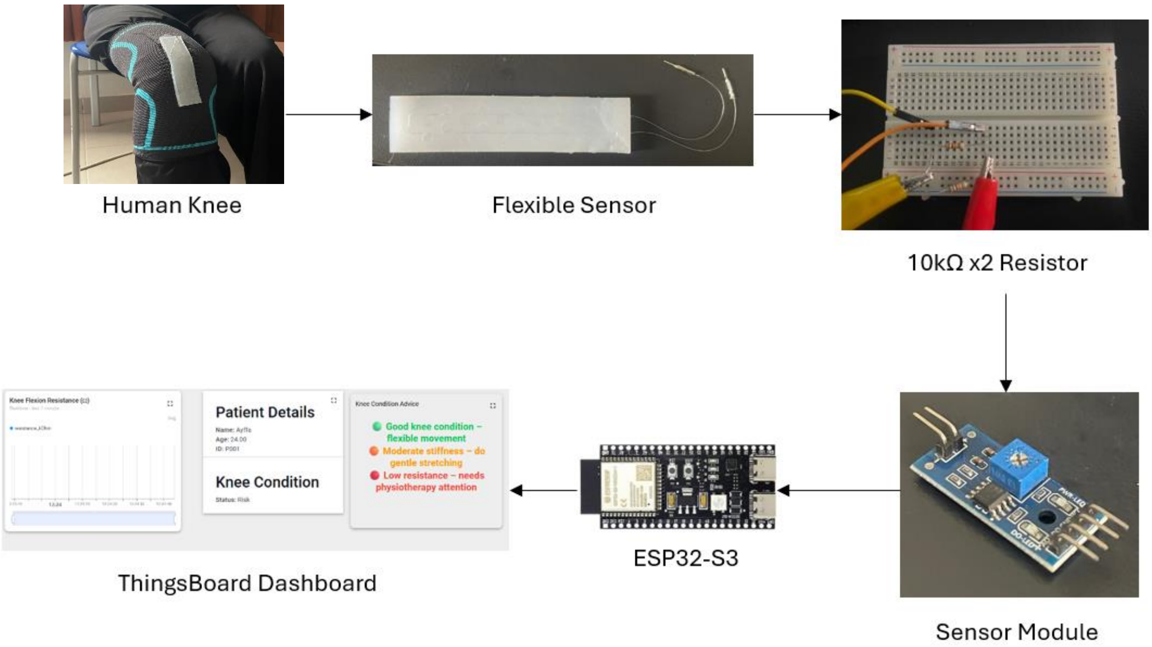

Fig 4 *Experimental setup of project*

During experimental evaluation, the developed flexible sensor was designed to produce measurable resistance variations in response to deformation occurring at the knee joint during movement. The sensor output was used to capture joint deformation associated with knee flexion, and the resulting data were analysed to assess sensor performance. For validation purposes, the resistance-based measurements obtained from the developed sensor were compared with joint angle measurements acquired using a goniometer to evaluate measurement consistency and accuracy. The sensor was mounted securely on the knee joint to ensure reliable deformation detection during movement, as illustrated in the experimental setup in Figure 5. The use of the developed sensor enables rehabilitation practitioners to measure knee movement more efficiently by reducing the time required for manual assessment. Furthermore, the integration of the wearable sensor

Fig 5 *Sensor attached on human knee*

3. Results and Discussion

The resistance and angle measurements in Table 1 were obtained using the flexible resistive sensor integrated into the wearable knee support. As the knee underwent flexion and extension, mechanical deformation of the conductive thread embedded in the flexible substrate produced corresponding changes in electrical resistance. These resistance values were acquired by the ESP32-S3 microcontroller through an analogue input and processed in real time. The measured resistance in Figure 5 showed a consistent relationship with knee bending, where increased flexion resulted in higher resistance values due to the stretching of the conductive thread.

Table 1 *The reading of angle and resistance measurement*

No.	Angle (∘)	Resistance (kΩ)
1	7.9	12.3
2	25.9	13.7
3	27.1	14.4
4	30	14.3
5	57	17.3
6	61	18.1

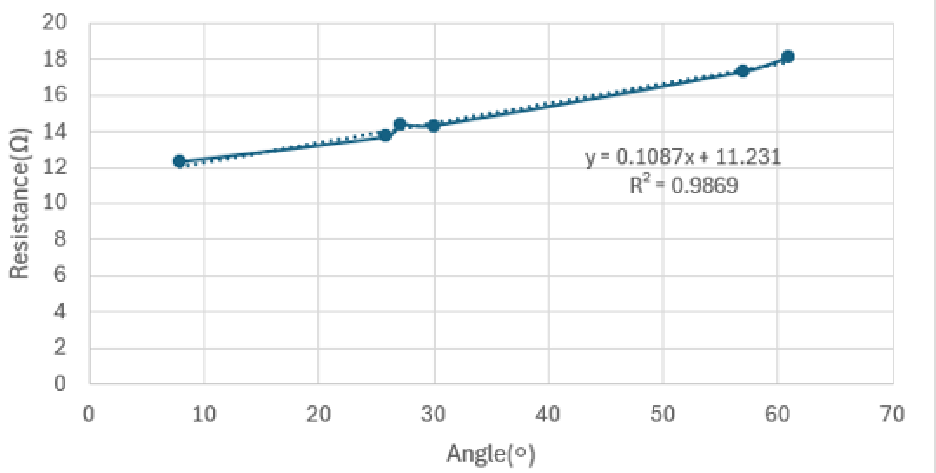

Fig 5 *The graph of angle and resistance measurement*

To evaluate angular measurement, the resistance data were correlated with knee flexion angles obtained during controlled human knee movement. The results demonstrated a clear and repeatable relationship between resistance variation and knee flexion angle, indicating stable sensor behaviour. In this project, the knee flexion angle was calculated using a linear calibration model expressed as Equation 1:

$$\boldsymbol{\Theta} = \boldsymbol{m\mathcal{R}} + \mathbf{c} \quad (1)$$

Where $\boldsymbol{\Theta}$ represents the knee flexion angle in degrees, (R) denotes the measured resistance of the flexible sensor in kilo-ohms (kΩ), (m) is the calibration gradient, and (c) is the offset constant determined during the calibration process.

The knee flexion angle was determined without manual measurement by performing an initial calibration procedure in which known knee positions were recorded to establish the resistance–angle relationship. Once the calibration parameters were obtained, subsequent knee flexion angles were estimated automatically in real time based solely on the measured resistance values. This approach eliminates the need for manual tools such as goniometers during operation and enables continuous, objective angle estimation suitable for real-time rehabilitation monitoring.

The experimental setup in Figure 6 for the results and discussion involved testing the developed wearable flexion monitoring system on human knee movement under controlled conditions. The flexible resistive sensor was securely attached to a wearable knee support and positioned along the knee joint to ensure consistent deformation during flexion and extension. The sensor was connected to the ESP32-S3 microcontroller via a voltage divider circuit for accurate resistance measurement. During the experiment, knee movements were performed gradually to capture stable resistance variations, which were transmitted wirelessly to the ThingsBoard dashboard. The data collected was used to analyze the relationship between resistance and knee flexion angle, as well as to evaluate the system's real-time visualization and knee condition assessment performance.

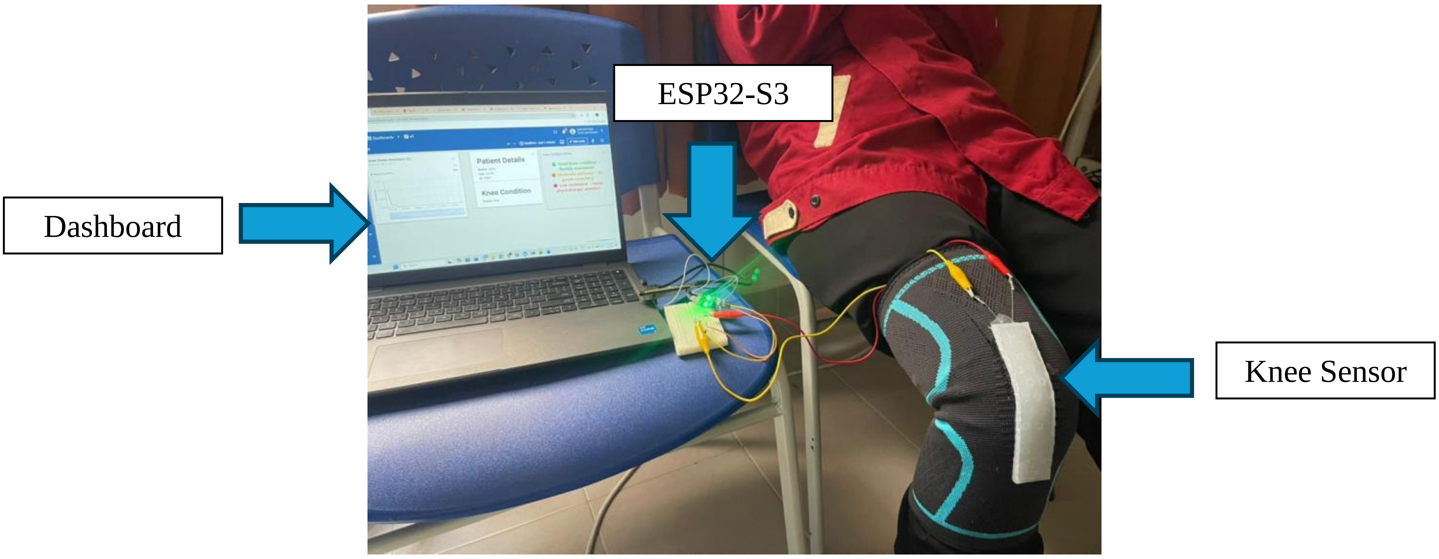

Fig 6 *Experimental Setup on human knee*

The wiring connection in Figure 6 of the system consists of the ESP32-S3 microcontroller interfaced with the flexible resistive sensor through a voltage divider circuit. The 5 V pin of the ESP32-S3 is connected to the VCC pin of the sensor module, while the GND pin is connected to the common ground. The analogue output (AO) of the sensor module is connected to an analogue input pin of the ESP32-S3 for resistance measurement. A 10 kΩ resistor is connected in series with the flexible sensor to form a voltage divider, enabling accurate detection of resistance changes during knee flexion. Jumper wires and clip leads are used to ensure stable electrical connections throughout the experiment.

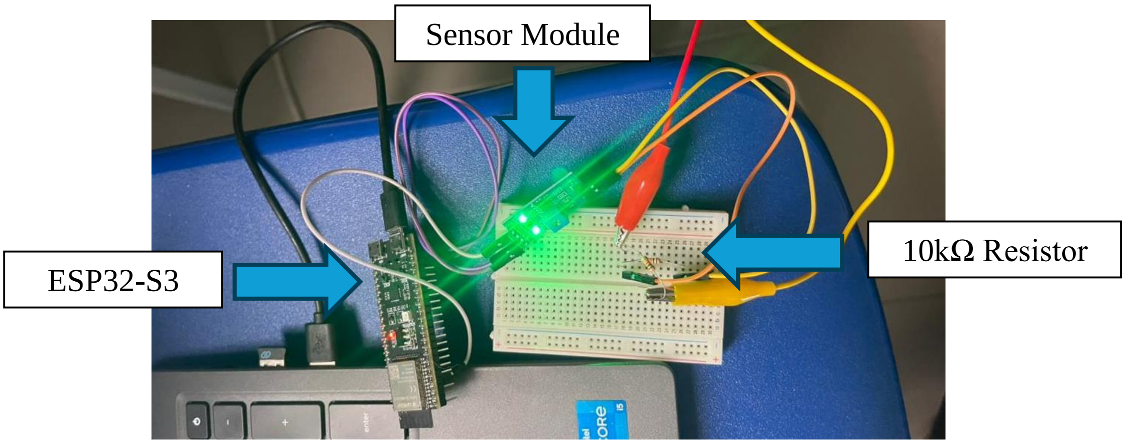

Fig 7 *The wiring connection of the setup*

Live streaming in Figure 8 was implemented to enable real-time monitoring of knee flexion data through a cloud-based ThingsBoard dashboard. The ESP32-S3 microcontroller continuously transmitted resistance data obtained from the flexible sensor to the cloud via a wireless connection. The incoming data were processed and displayed in real time using time-series graphs and numerical indicators, allowing continuous observation of resistance variation during knee movement. In addition to real-time visualization, the dashboard provided knee condition indicators based on predefined resistance thresholds, enabling immediate interpretation of knee performance including results in serial monitor in Figure 9. This live streaming capability supports continuous rehabilitation monitoring and facilitates timely assessment without the need for manual data retrieval.

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Fig 8 *The dashboard streaming results on patient knee*

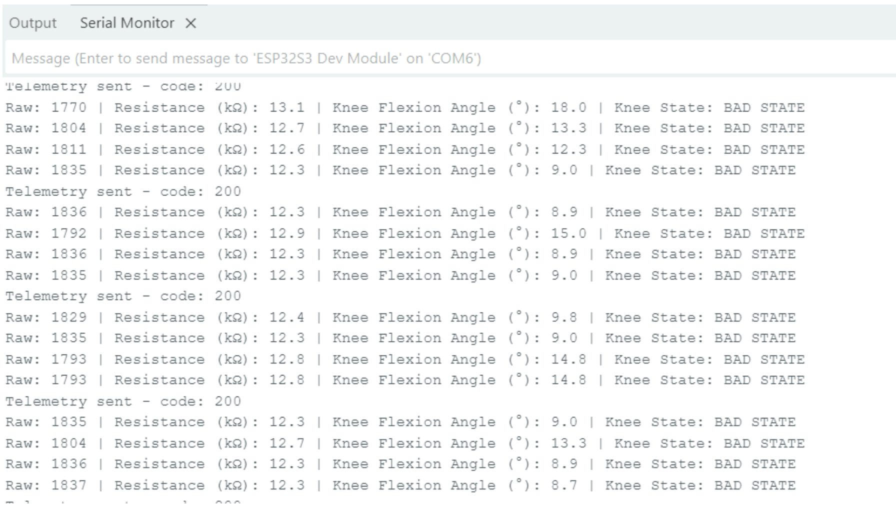

Fig 9 *The serial monitor from Arduino IDE*

The developed system combines a flexible resistive knee sensor, an ESP32-S3 microcontroller, and a cloud-based ThingsBoard dashboard to support real-time knee flexion monitoring. Sensor data are transmitted continuously to the cloud, where resistance values, patient information, and knee condition indicators are displayed simultaneously on the dashboard, allowing comprehensive observation of knee movement behaviour during monitoring sessions.

In Figure 9 shows the *Knee Flexion Resistance (Ω)* illustrates the variation of resistance with respect to time. When the knee remains in a relaxed or non-stretched position, minimal sensor deformation occurs, resulting in low and stable resistance values that appear as a relatively flat trend on the graph. During knee flexion, the conductive thread within the flexible sensor stretches along the knee joint, leading to an increase in resistance and the formation of a distinct peak on the graph. Each peak corresponds to a knee flexion event, while the subsequent decrease indicates the knee returning to an extended position. The magnitude of the peak reflects the degree of knee bending, enabling evaluation of movement intensity and consistency.

The peak points on the graph represent the instances of maximum knee flexion and provide useful temporal information, including the start of movement, the point of maximum bending, and the duration of each flexion cycle. This information is valuable for assessing rehabilitation performance, such as movement frequency, repetition consistency, and recovery progression. In addition to graphical visualization, the system automatically classifies knee condition based on predefined resistance thresholds. These conditions are displayed on the dashboard using colour-coded indicators, where green indicates normal movement, orange represents moderate stiffness, and red signifies abnormal readings that may require physiotherapy attention, allowing immediate interpretation without manual data analysis.

The serial monitor output further supports the results by displaying real-time raw sensor readings, calculated resistance values, estimated knee flexion angles, and the corresponding knee condition status for each measurement. Consistent and sequential data updates observed in the serial monitor confirm correct sensor operation, reliable data processing, and successful telemetry transmission to the cloud platform. Overall, the results demonstrate stable knee flexion detection, effective real-time visualization, and automated knee condition assessment, supporting objective monitoring for rehabilitation applications.

4. Conclusion

This study presented the development and evaluation of a wearable knee support sensor system for real-time knee flexion monitoring in rehabilitation applications. A flexible resistive sensor fabricated using conductive thread embedded within a flexible rubber substrate was successfully integrated with an ESP32-S3 microcontroller and a cloud-based ThingsBoard dashboard. The experimental results demonstrated a consistent and repeatable relationship between resistance variation and knee flexion angle, confirming the reliability of the sensing mechanism during human knee movement.

The real-time data visualization and knee condition classification provided by the dashboard enabled effective monitoring of knee movement behavior and immediate interpretation of rehabilitation status. The integration of live streaming and automated condition assessment reduced reliance on manual measurement and subjective evaluation. Overall, the findings indicate that the proposed system offers a practical and accessible approach for continuous knee rehabilitation monitoring, with potential applications in both clinical and home-based environments.

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References

Baek, Y. and Park, Y.L. (2024) "Flexible Wearable Joint Motion Sensor Based On Multi-Wire Displacement," in *2024 IEEE 7th International Conference on Soft Robotics, RoboSoft 2024*. Institute of Electrical and Electronics Engineers Inc., pp. 940–945. Available at: https://doi.org/10.1109/RoboSoft60065.2024.10521975.

Clark, N.C., 2025. Prehabilitation and rehabilitation for total knee replacement surgery: physiotherapy interventions in personalized medicine and charting a course towards optimal outcomes. *Orthopaedics and Trauma*, *39*(1), pp.65-73.

Dwiyaniti, M. *et al.* (2023) "IoT Monitoring System for Real-Time Temperature, Vibration, and Motor Speed on Overhead Crane," in *Proceedings - 2023 6th International Conference on Computer and Informatics Engineering: AI Trust, Risk and Security Management (AI Trism), IC2IE 2023*. Institute of Electrical and Electronics Engineers Inc., pp. 198–202. Available at: https://doi.org/10.1109/IC2IE60547.2023.10331590.

Forsyth, L. *et al.* (2024) "Validity of wearable sensors for total knee arthroplasty (TKA) rehabilitation: A study in younger and older healthy participants," *Knee*, 51, pp. 292–302. Available at: https://doi.org/10.1016/j.knee.2024.10.006.

Gu, Y. *et al.* (2023) "A Flexible Sensor and MIMU-Based Multisensor Wearable System for Human Motion Analysis," *IEEE Sensors Journal*, 23(4), pp. 4107–4117. Available at: https://doi.org/10.1109/JSEN.2022.3233653.

Kabir, P. *et al.* (2024) "An inflatable soft wearable knee rehabilitation device: Design, fabrication, control and preliminary evaluation," *Mechatronics*, 102, pp. 103233. Available at: https://doi.org/https://doi.org/10.1016/j.mechatronics.2024.103233.

Mafop, N. N., Abidin, A. Z., & Mohamad, H. (2024, July). IoT-Based Monitoring System for Indoor Air Quality using Thingsboard. In 2024 IEEE International Conference on Applied Electronics and Engineering (ICAEE) (pp. 1-6). IEEE.: https://doi.org/10.1109/ICAEE62924.2024.10667562.

Mustapha, N.H.M. *et al.* (2023) "DEVELOPMENT OF A STRETCHABLE CONDUCTIVE SENSOR FOR FLEXIBLE DEFORMATION: A PRELIMINARY STUDY," *Jurnal Teknologi*, 85(4), pp. 27–35. Available at: https://doi.org/10.11113/jurnalteknologi.v85.19107.

Nagarajapandian, M. *et al.* (2023) "Monitoring of Prosthetic Leg during Rehabilitation using IoT," in *Proceedings of the 2023 2nd International Conference on Augmented Intelligence and Sustainable Systems,* *ICAISS 2023*. Institute of Electrical and Electronics Engineers Inc., pp. 1552–1556. Available at: https://doi.org/10.1109/ICAISS58487.2023.10250532.

Qin, J., Tang, Y., Zeng, Y., Liu, X. and Tang, D., 2024. Recent advances in flexible sensors: From sensing materials to detection modes. *TrAC Trends in Analytical Chemistry*, *181*, p.118027.. Elsevier B.V. Available at: https://doi.org/10.1016/j.trac.2024.118027.

R.Kalaivani *et al.* (2025) "LabVIEW based Patient Monitoring System," in *2025 5th International Conference on Trends in Material Science and Inventive Materials (ICTMIM)*. IEEE, pp. 1711–1715. Available at: https://doi.org/10.1109/ICTMIM65579.2025.10988306.

Shetty, S., Maiya, G.A., Kg, M.R., Vijayan, S. and George, B.M., 2025. Quadriceps angle as an outcome measure for structural integrity following total knee arthroplasty in individuals with severe knee osteoarthritis. *Journal of Orthopaedics*, *61*, pp.37-42. Available at: https://doi.org/10.1016/j.jor.2024.09.010.

Singh, J., Garg, N., Sethuraman, R., Ghosh, S., Kumar, A.H. and Kolluri, R., 2024, July. Deploying Healthcare Monitoring System For Elderly Patient Care using IoT and Neural Network Techniques. In *2024 IEEE 3rd World Conference on Applied Intelligence and Computing (AIC)* (pp. 1179-1184). IEEE.." Available at: https://doi.org/10.1109/AIC.2024.193.

Suzumori, K. and Nabae, H. (2025) "Review of Flexible/Stretchable Sensors for Soft Robot," *Journal of Robotics and Mechatronics*. Fuji Technology Press, pp. 8–12. Available at: https://doi.org/10.20965/jrm.2025.p0008.

Wang, P. *et al.* (2022) "Flexible, stretchable, breathable and sweatproof all-nanofiber iontronic tactile sensor for continuous and comfortable knee joint motion monitoring," *Nano Energy*, 103, p. 107768. Available at: https://doi.org/https://doi.org/10.1016/j.nanoen.2022.107768.

Wei, D., Wang, Y., Chen, Z. and Zhong, L., 2025. Correlation study of kinesiophobia and functional rehabilitation after total knee arthroplasty. *Current Problems in Surgery*, *66*, p.101740.. Available at: https://doi.org/10.1016/j.cpsurg.2025.101740.

Yasser, A. and Solayman, M.M. (2024) "Computer-Based Machine Learning Model for Supporting and Healing ACL Injury for Athletes," in. Institute of Electrical and Electronics Engineers (IEEE), pp. 610–615. Available at: https://doi.org/10.1109/imsa61967.2024.10652749.

Zhu, D., Zhao, J., Wang, M., Cao, B., Zhang, W., Li, Y., Zhang, C. and Han, T., 2024. Rehabilitation applications based on behavioral therapy for people with knee osteoarthritis: systematic review. *JMIR mHealth and uHealth*, *12*(1), p.e53798.. Available at: https://doi.org/https://doi.org/10.2196/53798.