

Non-Invasive Smart Knee Support for Pain Relief and Mobility Enhancement

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Abstract- A Knee pain and mobility limitations are among the most prevalent musculoskeletal disorders affecting individuals across all age groups. This paper presents a non-invasive smart knee support system designed to provide real-time pain assessment, mobility enhancement, and preventive intervention. The system integrates wearable sensors, including motion and pressure sensors, to continuously monitor knee joint activity. An intelligent algorithm processes the collected data to estimate pain levels and detect abnormal movement patterns. Based on the analysis, the system delivers immediate haptic feedback to guide corrective actions. Furthermore, the integration of Internet of Things (IoT) technology enables remote monitoring, cloud-based data storage, and long-term analysis of joint performance. Experimental results demonstrate improved user awareness, reduced strain, and enhanced mobility. The proposed system offers a proactive, user-friendly, and efficient solution for personalized knee care and rehabilitation.

Keywords: Smart Knee Support, Wearable Sensors, Pain Assessment, IoT, Haptic Feedback, Rehabilitation.

I. INTRODUCTION

Knee joint disorders are among the most prevalent musculoskeletal conditions affecting individuals across diverse age groups. The knee serves as a critical load-bearing joint responsible for supporting body weight and enabling essential movements such as walking, running, and climbing. Any impairment in knee function can significantly reduce mobility, independence, and overall quality of life. Despite advances in medical science, existing treatment approaches remain largely reactive, addressing symptoms after they occur rather than preventing them through continuous monitoring and early intervention.

Traditional management techniques, including physiotherapy and medication, often depend on intermittent clinical assessments that fail to capture dynamic variations in joint behavior during daily activities. Patients may experience discomfort or abnormal movement patterns outside clinical settings, which remain undetected until symptoms worsen. Furthermore, subjective pain reporting introduces variability and inconsistency, limiting the accuracy of diagnosis and treatment planning.

Recent developments in wearable technology and sensor systems have created opportunities for continuous health monitoring beyond clinical environments. By integrating motion sensors, pressure sensors, and intelligent algorithms, it is possible to observe joint mechanics in real time and identify early signs of strain or dysfunction. This paper presents a smart knee support system that leverages these advancements to provide continuous monitoring, real-time feedback, and IoT-enabled remote analysis. The objective is not merely to detect knee problems but to actively assist users in maintaining safe movement patterns and preventing injury.

II. CONCEPTUAL BACKGROUND

The understanding of knee joint function and its associated disorders requires a multidisciplinary perspective that integrates biomechanics, physiology, and modern sensing technologies. The knee joint is one of the most complex and heavily loaded joints in the human body, playing a crucial role in maintaining posture, balance, and locomotion. It operates through coordinated interactions between bones, ligaments, tendons, and muscles, allowing flexion, extension, and slight

rotational movements. Due to its structural complexity and continuous exposure to mechanical stress, the knee is highly susceptible to injuries, degeneration, and chronic conditions such as osteoarthritis. These conditions often manifest as pain, stiffness, and reduced mobility, significantly impacting an individual's quality of life.

From a biomechanical standpoint, knee health is largely determined by the distribution of forces and motion patterns during physical activities. Normal joint function involves smooth articulation and balanced load distribution across the joint surfaces. However, deviations from normal movement patterns—such as improper gait, excessive load, or asymmetrical motion—can lead to abnormal stress concentrations, accelerating tissue damage and triggering pain responses. Traditional clinical assessments are limited in capturing these dynamic variations, as they are typically conducted in controlled environments and at discrete time intervals. Consequently, there is a growing need for systems capable of continuously monitoring joint behavior in real-world conditions.

Wearable sensor technology provides a promising solution to this challenge by enabling real-time acquisition of biomechanical data. Motion sensors, including accelerometers and gyroscopes, are capable of capturing angular displacement, velocity, and orientation of the knee joint during movement. These sensors provide valuable insights into gait patterns, joint angles, and dynamic stability. Complementing these are pressure sensors, which measure localized force distribution around the knee. Together, these sensing modalities offer a comprehensive representation of joint mechanics, allowing for the detection of subtle changes that may indicate the onset of discomfort or injury.

The concept of personalization is also central to modern healthcare solutions. Each individual exhibits unique movement patterns, physical characteristics, and levels of activity, necessitating tailored approaches to monitoring and intervention. By leveraging continuous data collection and adaptive algorithms, wearable systems can be customized to suit individual needs, improving both

effectiveness and user compliance. This personalized approach aligns with the broader trend toward patient-centered healthcare, where technology empowers individuals to actively participate in managing their own health.

III. LITERATURE REVIEW

The study by Nandhini et al. (2023) presents the development of an exoskeleton knee extension assist suspension brace aimed at reducing joint pain in elderly individuals. The authors emphasize the growing prevalence of osteoarthritis and its impact on mobility. The proposed system utilizes a lightweight and ergonomically designed wearable brace that provides controlled assistance during knee extension movements.

Divekar et al. (2025) introduced a task-agnostic knee exoskeleton designed to provide assistance across multiple daily activities such as walking, stair climbing, and standing. Unlike conventional devices, this system adapts dynamically using real-time joint kinematics and torque data. The pilot study demonstrated significant improvements in pain reduction, walking efficiency, and reduction in muscular fatigue among OA patients. The device features a lightweight structure and intelligent control algorithms that adjust assistance based on user activity and effort.

Wu et al. (2021) investigated the relationship between knee osteoarthritis pain and the mechanical properties of surrounding soft tissues. The study utilized non-invasive measurement techniques to assess stiffness, elasticity, and viscoelastic behavior of muscles, ligaments, and tendons around the knee joint. The findings revealed a strong correlation between increased pain levels and altered soft tissue mechanics, particularly increased stiffness and reduced elasticity. This suggests that biomechanical changes in periarticular tissues contribute significantly to pain perception and functional impairment. The authors propose that these mechanical properties can serve as early biomarkers for OA progression.

Priya et al. (2023) proposed a wearable pain management system that integrates sensors, microcontrollers, and therapeutic actuators to provide targeted interventions such as vibration therapy, heat application, and mild electrical stimulation. The system enables continuous monitoring of knee movement and delivers real-time, personalized therapy. Experimental results indicated significant reductions in pain and improvements in joint flexibility and functional performance.

Critcher et al. (2023) explored the use of localized multi-site bioimpedance measurements as a predictive tool for knee osteoarthritis pain. Sensors placed around the knee joint measure electrical properties of tissues, which reflect inflammation, fluid accumulation, and tissue degradation. The study demonstrated that variations in bioimpedance strongly correlate with pain intensity, enabling continuous and objective monitoring in free-living conditions. This approach provides a significant advantage over traditional clinical assessments by allowing real-time tracking of disease progression.

Teoh et al. (2023) proposed an advanced deep hybrid learning model for predicting pain severity in individuals with knee osteoarthritis using data obtained from the Osteoarthritis Initiative (OAI). The study integrates both machine learning and deep learning approaches to analyze multimodal datasets, including clinical information, imaging biomarkers, and biomechanical parameters.

The model architecture combines convolutional neural networks (CNNs) and long short-term memory (LSTM) networks to leverage both spatial and temporal data features. CNNs are employed to extract meaningful patterns from knee MRI images, enabling the identification of structural abnormalities associated with osteoarthritis. Meanwhile, LSTM networks are utilized to analyze time-series data such as patient-reported pain scores, physical activity levels, and disease progression trends.

IV. THEORETICAL FRAMEWORK

The design and operation of the proposed non-invasive smart knee support system are grounded in a combination of biomechanical principles, signal processing theory, and feedback control mechanisms. Unlike conventional assistive devices that provide passive support, the proposed system functions as an intelligent, adaptive platform that continuously interprets joint behavior and responds in real time. This approach requires a theoretical framework that explains how raw sensor data is transformed into meaningful indicators of knee health and how these indicators are used to guide corrective action.

At the core of the system lies the concept of biomechanical modeling of the knee joint. The knee can be considered a dynamic system in which forces, moments, and motion patterns interact to produce functional movement. During activities such as walking or climbing stairs, the joint experiences varying loads that are distributed across ligaments, cartilage, and surrounding tissues. Under normal conditions, these loads are balanced, allowing smooth and efficient motion. However, deviations such as uneven load distribution, excessive angular displacement, or irregular gait patterns can disrupt this balance, leading to localized stress and discomfort. The theoretical assumption underlying the proposed system is that such deviations can be detected through measurable changes in motion and pressure signals, providing an indirect yet reliable indication of pain or strain.

The acquisition of these signals is governed by principles of sensor fusion, where multiple sensing modalities are combined to obtain a more comprehensive understanding of joint behavior. Motion sensors, including accelerometers and gyroscopes, provide information about angular velocity, orientation, and acceleration, while pressure sensors capture force distribution across the knee. Individually, each sensor offers limited insight; however, when integrated, they enable a multidimensional representation of knee mechanics. The fusion of these data streams enhances accuracy and reduces uncertainty, allowing the system to

detect subtle abnormalities that may not be evident from a single parameter. This concept is essential for ensuring that the system can differentiate between normal variations in movement and patterns indicative of potential injury.

Once data is acquired, signal processing techniques are applied to extract meaningful features from raw sensor inputs. Noise filtering, normalization, and feature extraction are critical steps in this process, as sensor readings are often affected by environmental factors and motion artifacts. Filtering techniques, such as low-pass or Kalman filtering, are used to remove unwanted noise while preserving relevant information. The processed signals are then analyzed to identify key parameters, including joint angle variations, velocity changes, and pressure distribution patterns. These parameters serve as inputs to the decision-making algorithm, forming the basis for evaluating joint condition.

The decision-making process is modeled using threshold-based and pattern recognition approaches. Threshold-based analysis involves defining acceptable ranges for various parameters, beyond which the system interprets the condition as abnormal. For example, excessive pressure on a specific region or abnormal angular deviation may indicate strain. Pattern recognition techniques further enhance this process by identifying recurring movement patterns associated with discomfort or improper posture. Together, these approaches enable the system to classify joint behavior into normal and abnormal states, providing an objective assessment of potential pain levels.

V. PROPOSED SYSTEM

The proposed non-invasive smart knee support system is designed as an integrated, intelligent wearable solution that combines real-time sensing, data processing, feedback mechanisms, and IoT-based connectivity to address the limitations of conventional knee care approaches. Unlike traditional knee braces or rehabilitation devices that provide passive support, the proposed system actively monitors joint behavior, interprets biomechanical signals, and delivers immediate

corrective feedback. This proactive approach transforms the device from a supportive accessory into an interactive healthcare system capable of assisting users in maintaining optimal movement patterns and preventing injury.

At the foundation of the system is a multi-sensor architecture that captures comprehensive biomechanical data related to knee joint activity. Motion sensors, including accelerometers and gyroscopes, are employed to measure angular displacement, velocity, and orientation of the knee during movement. These sensors provide continuous information about dynamic motion patterns such as flexion, extension, and rotational behavior. In parallel, pressure sensors are strategically positioned around the knee joint to measure localized force distribution. These sensors detect variations in load, enabling identification of uneven stress concentrations that may indicate improper posture, excessive strain, or the onset of discomfort. The combination of motion and pressure sensing ensures that the system captures both kinematic and kinetic aspects of joint behavior, providing a holistic understanding of knee mechanics.

The data collected from the sensor module is transmitted to the central processing unit, implemented using an ESP32 microcontroller. The ESP32 is selected due to its high computational capability, low power consumption, and built-in wireless communication features, making it suitable for wearable IoT applications. Within the processing unit, raw sensor data undergoes a series of preprocessing steps, including noise filtering, signal normalization, and feature extraction. These steps are essential for ensuring the accuracy and reliability of the data, as wearable sensors are often subject to environmental disturbances and motion artifacts.

Following preprocessing, the system employs an intelligent decision-making algorithm to analyze the processed data and evaluate the condition of the knee joint. The algorithm operates by comparing real-time sensor readings with predefined thresholds and learned patterns representing normal movement behavior. Deviations from these patterns

are interpreted as indicators of abnormal joint activity, which may correspond to increased strain or potential pain. The algorithm is designed to differentiate between harmless variations in movement and critical conditions that require intervention, thereby minimizing false alarms while ensuring timely detection of harmful patterns.

A key feature of the proposed system is its real-time feedback mechanism, which operates as part of a closed-loop control system. When the algorithm detects abnormal movement or excessive pressure, the system activates a haptic feedback module to alert the user. This feedback is typically delivered in the form of controlled vibration signals, which are intuitive and non-intrusive. The purpose of this feedback is to prompt the user to adjust their posture, redistribute load, or modify their movement pattern. By providing immediate guidance, the system helps prevent further strain and encourages safer movement habits. Over time, this continuous feedback contributes to behavioral adaptation, enabling users to develop improved motor patterns and reduce the likelihood of injury.

VI. BLOCK DIAGRAM

- **Power Supply Unit:** Provides regulated power to all system components.
- **ESP32 Microcontroller:** Processes sensor data and controls outputs using TinyML.
- **Flex Sensor:** Detects knee bending by measuring resistance change.
- **Force Sensor:** Measures pressure applied on the knee joint.
- **ADXL345 Sensor:** Detects motion, tilt, and acceleration of movement.
- **LCD Display:** Shows real-time sensor data and system status.
- **Vibrator Motor:** Gives haptic feedback when abnormal conditions are detected.
- **IoT (WiFi - ESP32):** Sends data wirelessly to a mobile application.
- **Mobile App:** Displays monitored data and alerts to the user.

VII. METHODOLOGY

The methodology of the proposed non-invasive smart knee support system is structured as a systematic and continuous process that integrates data acquisition, signal processing, intelligent analysis, feedback generation, and IoT-based communication. The overall objective of this methodology is to ensure accurate monitoring of knee joint behavior, timely detection of abnormal conditions, and immediate intervention to prevent further strain or injury. The system operates as a closed-loop framework, where each stage contributes to real-time assessment and adaptive response, enabling both short-term correction and long-term improvement in mobility.

The first stage of the methodology involves data acquisition through wearable sensors positioned around the knee joint. Motion sensors, such as accelerometers and gyroscopes, are employed to capture dynamic parameters including angular displacement, velocity, and orientation of the knee during various activities. These sensors continuously monitor the movement patterns associated with flexion, extension, and rotational motion. Simultaneously, pressure sensors are utilized to measure localized force distribution across the knee joint, providing insights into load-bearing conditions and identifying areas subjected to excessive stress. The placement of these sensors is carefully optimized to ensure accurate data collection while maintaining user comfort and minimizing interference with natural movement. The continuous acquisition of multi-dimensional data forms the foundation for subsequent analysis and decision-making.

Following data acquisition, the methodology proceeds to the signal preprocessing stage, where raw sensor data is conditioned to improve accuracy and reliability. Wearable sensor signals are often affected by noise, motion artifacts, and environmental disturbances, which can lead to inaccurate interpretations if not properly addressed. To mitigate these effects, filtering techniques such as low-pass filtering or moving average methods are applied to remove high-frequency noise while

preserving essential signal characteristics. In addition, normalization techniques are employed to standardize the data, ensuring consistency across different users and operating conditions. This preprocessing step is critical for enhancing the quality of the data and enabling precise feature extraction.

The next stage involves feature extraction and data analysis, where meaningful parameters are derived from the processed signals. Key features such as joint angle variation, rate of movement, pressure distribution patterns, and temporal changes in these parameters are identified and quantified. These features provide a comprehensive representation of knee joint behavior and serve as inputs to the decision-making algorithm. The analysis focuses on detecting deviations from normal movement patterns, which may indicate improper posture, excessive load, or the onset of discomfort. By examining both kinematic and kinetic data, the system achieves a more accurate and holistic assessment of joint condition.

The decision-making stage is implemented through an intelligent algorithm that evaluates the extracted features against predefined thresholds and learned behavioral patterns. The algorithm is designed to classify the current state of the knee joint as either normal or abnormal based on the observed data. Threshold values are determined through experimental calibration and are adjusted to accommodate variations in user characteristics. In addition to threshold-based evaluation, pattern recognition techniques are employed to identify recurring movement anomalies that may not be captured by static thresholds alone. This dual approach enhances the robustness of the system, allowing it to accurately detect conditions that require intervention while minimizing false detections.

Once an abnormal condition is identified, the methodology transitions to the feedback generation stage, which is a critical component of the system's closed-loop operation. The system activates a haptic feedback module to deliver immediate alerts to the user. The feedback is typically provided in the form

of vibration signals, which are designed to be intuitive, noticeable, and non-intrusive. The purpose of this feedback is to prompt the user to adjust their posture, redistribute load, or modify movement patterns in real time. This immediate intervention helps prevent further strain and encourages the adoption of safer movement behaviors. Over time, repeated exposure to feedback leads to behavioral adaptation, improving overall joint stability and mobility.

In parallel with local processing and feedback, the methodology incorporates an IoT-based communication stage that enables remote monitoring and data management. The processed data, along with relevant indicators such as detected abnormalities and feedback events, is transmitted to a cloud-based platform using the wireless capabilities of the ESP32 microcontroller. This data is stored and organized for long-term analysis, allowing both users and healthcare professionals to access historical records and identify trends in joint performance. The cloud platform supports visualization tools that provide insights into movement patterns, frequency of abnormal events, and progress over time. This capability is particularly valuable for rehabilitation, where continuous monitoring can inform personalized treatment strategies and improve clinical outcomes.

Furthermore, the methodology emphasizes user-centered design and adaptability. The system is capable of adjusting its parameters based on individual user profiles, taking into account factors such as baseline movement patterns, activity levels, and physical condition. This personalization enhances the accuracy of detection and ensures that feedback is relevant and effective for each user. The adaptability of the methodology also allows for future integration of advanced techniques, such as machine learning algorithms, which can further improve the system's predictive capabilities.

the methodology of the proposed smart knee support system is a comprehensive and structured approach that integrates sensing, processing, analysis, feedback, and connectivity into a unified framework. Each stage of the methodology is

designed to ensure accurate data interpretation, timely intervention, and continuous monitoring of knee joint activity. By operating as a closed-loop system with IoT-enabled capabilities, the methodology not only addresses immediate mobility challenges but also supports long-term musculoskeletal health and personalized rehabilitation.

VIII. RESULTS AND DISCUSSION

The performance of the proposed non-invasive smart knee support system was evaluated through experimental testing under various movement conditions, including walking, stair climbing, and controlled rehabilitation exercises. The primary objective of this evaluation was to assess the system's ability to accurately monitor knee joint behavior, detect abnormal movement patterns, estimate potential pain levels, and provide timely feedback to the user. The results demonstrate that the integration of multi-sensor data acquisition, intelligent processing, and real-time feedback significantly enhances both the accuracy of monitoring and the effectiveness of intervention.

The motion sensors, consisting of accelerometers and gyroscopes, were able to capture detailed information about joint angles, angular velocity, and movement patterns during different activities. The data obtained from these sensors showed consistent and reliable tracking of knee motion, allowing the system to distinguish between normal and irregular movement patterns. Similarly, the pressure sensors provided valuable insights into load distribution across the knee joint. Variations in pressure readings were observed during different phases of movement, particularly during weight-bearing activities, enabling the detection of uneven load distribution and excessive stress. The combination of motion and pressure data resulted in a comprehensive representation of knee mechanics, validating the effectiveness of the sensor fusion approach.

The preprocessing and analysis stages played a crucial role in improving data accuracy and reliability. Noise filtering techniques successfully minimized

signal disturbances caused by external factors and sensor limitations. Feature extraction methods enabled the identification of key parameters such as joint angle deviations and pressure concentration points. These parameters were used by the decision-making algorithm to evaluate joint condition in real time. The algorithm demonstrated high sensitivity in detecting abnormal conditions, such as excessive angular displacement or localized pressure spikes, which are indicative of potential strain or discomfort. At the same time, the system maintained a low rate of false detections, ensuring that feedback was provided only when necessary.

One of the most significant outcomes of the study is the effectiveness of the real-time feedback mechanism. The haptic feedback module responded immediately when abnormal conditions were detected, delivering vibration signals that prompted users to adjust their posture or movement. Observations indicated that users were able to quickly respond to these alerts, resulting in immediate correction of improper movement patterns. This real-time interaction between the system and the user highlights the importance of feedback-driven intervention in preventing further strain and promoting safer mobility. Over repeated trials, users exhibited improved movement consistency and reduced occurrence of abnormal patterns, suggesting that the system contributes to behavioral adaptation and long-term improvement in joint function.

The results also highlight the potential of the system to support both preventive and rehabilitative healthcare. In preventive scenarios, the system can identify early signs of strain and provide immediate feedback, reducing the likelihood of injury. In rehabilitation contexts, it serves as a monitoring and guidance tool, helping patients maintain correct movement patterns and track their progress over time. The adaptability of the system allows it to cater to a wide range of users, from athletes seeking performance optimization to elderly individuals requiring mobility support.

IX. CONCLUSION

The proposed non-invasive smart knee support system provides an effective solution for monitoring knee joint activity and managing pain. It overcomes the limitations of traditional methods by enabling continuous and objective assessment of movement. The integration of motion and pressure sensors allows accurate detection of abnormal patterns. This helps in identifying early signs of strain before they become serious issues. Overall, the system supports proactive and preventive knee care.

The real-time feedback mechanism plays a vital role in improving user movement. Haptic alerts guide users to correct posture and avoid harmful movements instantly. This immediate response reduces the risk of further injury and enhances safety. Over time, users develop better movement habits through continuous feedback. Thus, the system contributes to long-term improvement in mobility and joint stability.

The incorporation of IoT technology enhances the system's capabilities beyond local monitoring. Data is stored and analyzed in the cloud, enabling remote access for healthcare professionals. This allows tracking of rehabilitation progress and better decision-making. Long-term data analysis provides insights into user activity and joint performance. Hence, the system supports personalized and data-driven healthcare.

In conclusion, the smart knee support system combines sensing, analysis, feedback, and connectivity into a single platform. It improves mobility, reduces pain, and promotes safe movement in daily life. The wearable design ensures comfort and ease of use for continuous monitoring. The system has strong potential for both personal and clinical applications. It represents a significant step toward advanced wearable healthcare solutions.

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