REAL TIME BASED PRESSURE MEASUREMENT DEVICE TO OPTIMIZE ORTHOTIC DESIGN AND PATIENT OUTCOMES

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Abstract

Orthotic devices play a crucial role in correcting biomechanical abnormalities, redistributing plantar pressure, and improving patient mobility and comfort. However, conventional orthotic design methods largely rely on static measurements and subjective clinical assessments, which may not accurately capture real-time pressure variations during dynamic activities such as walking or standing. This paper presents the design and development of a real-time pressure measurement system aimed at optimizing orthotic design and enhancing patient outcomes. The proposed system integrates flexible pressure sensors embedded within an orthotic insole, a microcontroller-based data acquisition unit, and wireless communication for real-time data transmission. The acquired pressure data is processed to extract key parameters such as peak pressure, pressure distribution, contact time, and center of pressure. The processed data is visualized on a cloud-based platform, enabling clinicians to analyze gait patterns and pressure maps effectively. Experimental results demonstrate that the proposed system provides accurate, reliable, and real-time plantar pressure measurements, making it a valuable tool for personalized orthotic design and continuous patient monitoring.

Keywords: Real-time pressure measurement, Orthotic design, Plantar pressure, Wearable sensors, Patient outcomes.

Introduction

Disorders associated with the human foot, such as flat foot deformity, diabetic foot ulceration, plantar fasciitis, and gait irregularities, represent a major clinical concern worldwide. These conditions often lead to persistent pain, instability, reduced mobility, and in severe cases, permanent disability. In individuals with diabetes, abnormal plantar pressure distribution significantly increases the risk of ulcer formation due to repetitive mechanical stress and reduced tissue tolerance. Similarly, biomechanical misalignment in flat feet or abnormal gait patterns results in uneven load distribution, accelerating tissue fatigue and structural damage. Therefore, accurate assessment and correction of plantar pressure abnormalities are essential for preventive healthcare and long-term rehabilitation. Plantar pressure plays a critical role in understanding foot biomechanics during static posture and dynamic activities such as walking or running. Excessive localized pressure, particularly under the heel and metatarsal heads, can cause microtrauma that gradually progresses into chronic injury. Continuous exposure to abnormal stress concentrations may lead to inflammation, soft tissue breakdown, and impaired locomotion. Early identification of these high-pressure zones enables clinicians to intervene before complications become severe. Orthotic devices are widely prescribed to correct foot alignment, redistribute plantar loads, enhance stability, and alleviate discomfort. The therapeutic effectiveness of an orthotic device, however, strongly depends on its ability to accurately adapt to the patient's unique foot structure and dynamic pressure characteristics. Conventional orthotic assessment techniques—including footprint impressions, visual gait inspection, and static pressure plate analysis—provide only limited information. These traditional approaches are often subjective, lack dynamic measurement capability, and fail to capture real-time variations occurring throughout the gait cycle. Consequently, orthotics designed using such methods may not optimally address patient-specific pressure concentrations, resulting in discomfort or suboptimal clinical outcomes. Recent advancements in flexible sensing technologies, low-power embedded systems, and wireless communication networks have opened new possibilities for wearable biomedical monitoring. Flexible Force Sensitive Resistors (FSRs), capacitive sensors, and piezoelectric materials now enable integration of lightweight and unobtrusive sensing elements within footwear. Simultaneously, microcontroller platforms with high-speed data acquisition and digital signal processing capabilities facilitate real-time analysis of biomechanical parameters. Cloud-based computing and Internet of Things (IoT) frameworks further enhance remote monitoring, long-term data storage, and intelligent visualization. Real-time plantar pressure monitoring systems provide continuous, quantitative insight into pressure distribution patterns and gait dynamics. Unlike static measurement approaches, dynamic sensing captures transient loading variations, stance-to-swing transitions, and center of pressure (CoP) progression during walking. These data allow clinicians to evaluate orthotic performance under realistic conditions and iteratively refine device design. Moreover, statistical analysis of repeated gait cycles enables objective validation of pressure redistribution effectiveness.

Related Works

The study of plantar pressure monitoring has gained significant attention in recent years due to its importance in diagnosing foot-related disorders, improving gait analysis, and preventing complications such as diabetic foot ulcers. Various approaches have been proposed in literature, ranging from conventional clinical systems to modern wearable sensor-based solutions.

Early research in plantar pressure analysis primarily relied on force plates and pressure mats, which provided highly accurate measurements of ground reaction forces and pressure distribution. These systems were widely used in gait laboratories and rehabilitation centers. However, their major limitations include high cost, bulky setup, and lack of portability, making them unsuitable for continuous or real-time monitoring in daily life environments.

To overcome these limitations, researchers introduced in-shoe pressure measurement systems using force-sensitive resistors (FSRs) and capacitive sensors. These systems enabled pressure sensing at multiple areas of the foot, allowing detailed mapping of pressure distribution during walking or standing. Studies demonstrated that such wearable systems significantly improved patient mobility tracking and offered more practical solutions compared to stationary platforms. However, challenges such as sensor drift, limited durability, and calibration complexity were reported.

With advancements in embedded systems, microcontroller-based solutions have been widely explored. Platforms such as the Arduino Uno and ESP32 have been utilized to develop low-cost and portable plantar pressure monitoring systems. These systems collect sensor data, process it in real time, and provide outputs through displays or wireless communication. The integration of wireless technologies such as Bluetooth and Wi-Fi has enabled remote monitoring and data logging, enhancing the usability of these systems in telemedicine applications.

Recent studies have also emphasized the importance of multi-parameter monitoring, particularly the combination of pressure and temperature sensing. Research indicates that localized temperature rise in the foot can serve as an early indicator of inflammation or ulcer formation, especially in diabetic patients. Systems incorporating both pressure sensors and temperature sensors have shown improved diagnostic capability compared to pressure-only systems.

Machine learning techniques have also been explored in advanced research for pattern recognition and anomaly detection in plantar pressure data. These approaches aim to classify gait abnormalities, detect high-risk regions, and predict potential injuries. Although promising, such systems often require large datasets, high computational resources, and complex model training, limiting their practical implementation in low-cost embedded devices.

Despite these advancements, several limitations still exist in current solutions. Many systems either focus on high accuracy with expensive hardware or low-cost implementations with limited functionality. Issues such as real-time visualization, ease of use, power consumption, and system integration remain key challenges.

The proposed system addresses these gaps by developing a cost-effective, real-time plantar pressure monitoring solution using multiple force sensors, a temperature sensor, and an ESP32 microcontroller. The system emphasizes simplicity, portability, and efficient data visualization through an LCD display, making it suitable for both clinical and personal healthcare applications.

Methodology

The proposed Plantar Pressure Monitoring System is designed to acquire, process, and analyze real-time plantar pressure and temperature data using an embedded system architecture. The methodology integrates hardware design, sensor calibration, data acquisition, signal processing, and output visualization to ensure accurate and reliable monitoring.

System Architecture

The proposed Plantar Pressure Monitoring System is designed using a structured and modular architecture that enables efficient acquisition, processing, and visualization of plantar pressure and temperature data in real time. The architecture integrates multiple hardware components and follows a layered approach to ensure scalability, reliability, and ease of implementation. The system primarily consists of sensing elements, a central processing unit, output interfaces, and a regulated power supply, with an optional communication module for remote monitoring.

The signals generated by the sensors are forwarded to the data acquisition and processing layer, which is centered around the ESP32. This microcontroller serves as the core computational unit of the system due to its high processing capability, integrated analog-to-digital converters (ADC), and built-in wireless communication features. The analog outputs from the force and temperature sensors are first passed through appropriate signal conditioning circuits, typically implemented using voltage divider configurations, to ensure that the signals are within the acceptable input range of the ESP32. The ADC within the microcontroller then converts these analog signals into digital values for further processing.

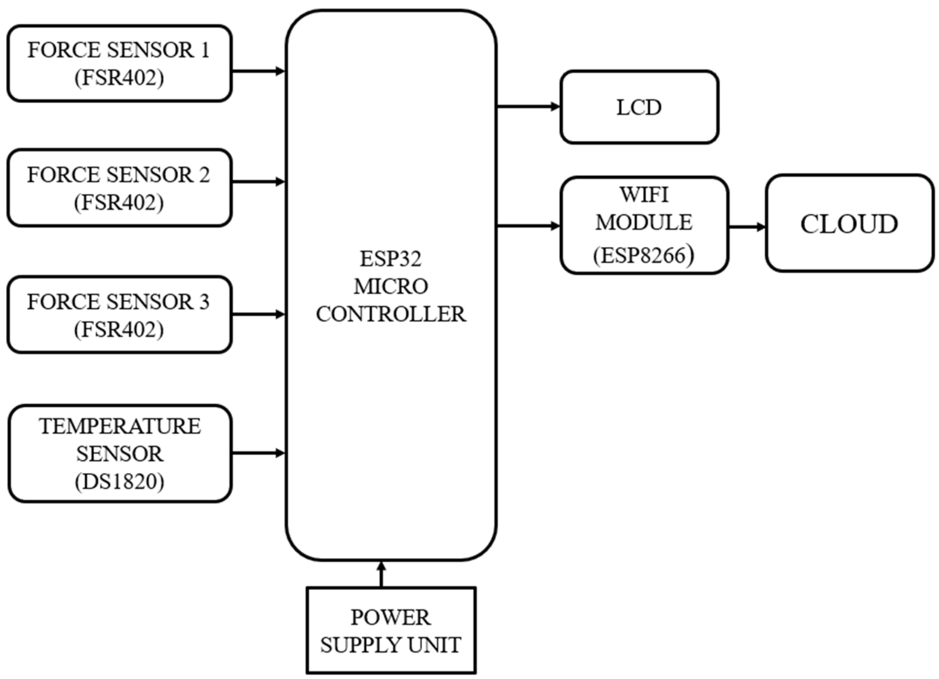

Figure 1: System Architecture

Sensing Layer

The sensing layer forms the foundation of the system and is responsible for capturing physical parameters from the plantar surface of the foot. Multiple force-sensitive resistors (FSRs) are strategically placed at key pressure points such as the heel, midfoot, forefoot, and toes. These regions are selected based on their significance in human gait and load distribution. Each force sensor operates by changing its resistance in response to applied force, thereby generating an analog signal proportional to the pressure exerted on that specific region.

In addition to pressure sensing, a temperature sensor is integrated into the system to monitor the thermal condition of the foot. The inclusion of temperature measurement is crucial for identifying abnormal temperature variations that may indicate inflammation, infection, or the early stages of diabetic foot ulcers. Together, the force sensors and temperature sensor provide comprehensive data for effective analysis.

Data Acquisition and Signal Conditioning

The signals obtained from the sensors are analog in nature and require proper conditioning before processing. Each force sensor is connected through a voltage divider circuit to convert resistance variations into measurable voltage signals. These signals are then stabilized using basic filtering techniques to reduce noise and fluctuations caused by environmental or mechanical disturbances.

The conditioned signals are fed into the analog input pins of the ESP32. The built-in Analog-to-Digital Converter (ADC) of the ESP32 converts these analog signals into digital values. This stage ensures that the raw sensor data is accurately captured and prepared for further processing.

Communication Layer

To enhance system functionality, an optional communication layer is incorporated using the built-in Wi-Fi and Bluetooth capabilities of the ESP32. This layer allows the system to transmit data to external devices such as smartphones, computers, or cloud platforms. Remote data transmission enables long-term monitoring, storage, and advanced analysis of plantar pressure patterns.

This feature is particularly useful in telemedicine applications, where healthcare professionals can monitor patients remotely and provide timely medical guidance. The communication layer thus extends the usability of the system beyond local monitoring.

Power Supply Layer

The entire system is powered by a regulated power supply unit that ensures stable and reliable operation. Proper voltage regulation is essential to maintain the accuracy of sensor readings and prevent fluctuations that could affect system performance. The power supply is designed to support all components, including sensors, the ESP32 microcontroller, and the LCD display, while maintaining energy efficiency.

Cloud Technology

Cloud technology plays a crucial role in enhancing the functionality and scalability of the proposed Plantar Pressure Monitoring System by enabling real-time data storage, remote access, and advanced analysis. The integration of cloud computing transforms the system from a standalone embedded device into a connected healthcare solution capable of continuous monitoring. By utilizing cloud infrastructure, the data collected from sensors can be accessed anytime and from anywhere, thereby improving the efficiency of medical diagnosis and patient care.

In the proposed system, the ESP32 serves as the interface between the sensing unit and the cloud platform. The ESP32 collects pressure and temperature data from the sensors and transmits it to the cloud server through its built-in Wi-Fi capability. Communication is established using standard internet protocols such as HTTP or MQTT, ensuring reliable and efficient data transfer. The transmitted data typically includes pressure values from different regions of the foot, temperature readings, and corresponding timestamps, allowing continuous tracking of the user's condition.

Local Monitoring and Display

In addition to cloud monitoring, the system also provides local monitoring through a 16×2 LCD display. The display shows real-time system information such as current values and system status.

During normal operation, the LCD displays the current flow and system condition. When a fault occurs, the display shows fault alerts and indicates that the circuit has been disconnected. This feature allows operators to quickly identify system status without accessing the cloud platform.

ARDUINO IDE

In this project, the Arduino IDE is utilized to write embedded C/C++ code that continuously reads analog inputs from multiple force-sensitive resistors (FSRs) placed at different regions of the foot, including the heel, midfoot, forefoot, and toes. These sensors produce varying voltage signals based on the applied pressure, which are captured through the ADC channels of the ESP32. The Arduino program processes these inputs using predefined logic to convert raw sensor values into meaningful pressure levels. Additionally, a temperature sensor is interfaced through the Arduino IDE, enabling the system to monitor foot temperature alongside pressure distribution.

The firmware developed in the Arduino IDE follows a structured approach using the setup() and loop() functions. During the initialization phase, all sensors, input pins, and the LCD module are configured. In the continuous execution phase, the system repeatedly reads sensor values, applies filtering techniques such as averaging to reduce noise, and performs calibration to improve accuracy. The processed data is then formatted and displayed on the LCD, providing real-time feedback to the user. This continuous loop ensures uninterrupted monitoring of plantar conditions.

Conclusion

The proposed Plantar Pressure Monitoring System successfully demonstrates an effective and low-cost solution for real-time monitoring of foot pressure distribution and temperature variations. The system integrates multiple force sensors and a temperature sensor with the ESP32 to provide accurate data acquisition, processing, and visualization. By combining embedded system design with biomedical sensing, the project addresses the growing need for accessible and continuous foot health monitoring.

The developed system is capable of identifying pressure distribution across key regions of the foot, enabling the detection of abnormal loading patterns that may lead to conditions such as foot ulcers, gait imbalance, and plantar stress injuries. The inclusion of temperature monitoring further enhances the system's diagnostic capability, as localized temperature variations can serve as early indicators of inflammation or tissue damage, particularly in diabetic patients.

One of the major contributions of this work is the design of a portable and user-friendly system that overcomes the limitations of conventional plantar pressure measurement techniques, which are often expensive, bulky, and restricted to laboratory environments. The use of an embedded platform ensures real-time processing, while the LCD interface allows immediate interpretation of results without the need for complex external systems. Additionally, the optional wireless communication capability provides scope for remote monitoring and integration with modern healthcare applications.

The system also emphasizes reliability through proper sensor placement, calibration techniques, and noise reduction methods, ensuring consistent and meaningful data output. Although the current implementation provides a functional and efficient prototype, certain limitations exist, such as dependency on sensor accuracy, limited spatial resolution due to a finite number of sensors, and the absence of advanced data analytics.

Future enhancements can focus on increasing the number of sensors for higher resolution pressure mapping, integrating machine learning algorithms for predictive analysis, and developing mobile or cloud-based platforms for long-term data storage and remote diagnosis. The incorporation of flexible and wearable sensor materials can further improve user comfort and system adaptability.

In conclusion, the proposed system highlights the potential of embedded and sensor-based technologies in transforming healthcare monitoring. It provides a practical approach for early detection, prevention, and management of foot-related disorders, thereby contributing to improved patient care and quality of life.

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