

# A Modular Sensing Insole System for Enhanced Gait Analysis and Foot Health Monitoring

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## Abstract

Plantar pressure measurement is an integral aspect of biomedical engineering, providing important insights for diagnosing and managing foot-related health conditions. This study introduces a modular piezoelectric sensing insole designed for enhanced human gait analysis. The system incorporates force-sensitive resistors strategically placed to capture dynamic plantar pressure data, which is processed and visualized using Python-based tools. Emphasizing portability, cost-effectiveness, and real-time analysis, the system identifies abnormal pressure distributions and classifies foot conditions. By integrating machine learning algorithm XGBoost, the solution provides actionable insights, aiding healthcare professionals in early diagnosis and preventive interventions. This approach offers substantial benefits in clinical settings, sports science, and rehabilitation, bridging the gap between technology and personalized healthcare.

**Keywords:** Plantar Pressure Measurement, Gait Analysis, XGBoost, Biomedical Engineering, Real-time Visualization, Preventive Healthcare.

## 1. Introduction

Human gait analysis studies movement patterns, focusing on walking and running, to diagnose mobility issues, enhance athletic performance, and design ergonomic footwear.

Traditional systems like motion capture and force plates are costly and limited to labs, restricting continuous monitoring. Sensor-based insoles equipped with Force-Sensitive Resistors (FSRs) offer a portable, real-time alternative. These lightweight and flexible insoles capture pressure variations across the foot, providing detailed insights into gait and force distribution. Their modular design supports customization for applications like rehabilitation and sports performance. Prediction algorithms enable immediate feedback, pattern detection, and actionable insights, making advanced gait analysis accessible and cost-effective. This innovative solution enhances health, performance, and injury prevention.

## 1.1 Background of the Problem

Plantar pressure measurement is essential in biomedical engineering, offering valuable insights into foot biomechanics and health conditions such as Diabetic Foot Ulcers (DFU) and Diabetic Sensorimotor Polyneuropathy (DSPN). According to studies, DFU affects approximately 15% of individuals with diabetes during their lifetime, significantly contributing to mobility issues and increased healthcare costs[1][3]. DSPN, prevalent in 50% of diabetic patients, impairs sensory feedback, causing patients to be unaware of abnormal pressure distribution and resulting injuries plantar pressure distribution exacerbates these conditions, leading to secondary complications such as infections and chronic ulcers[5]. For instance, high-pressure zones at the metatarsals and heel are linked to conditions like metatarsalgia and heel spurs. These complications incur significant healthcare costs; diabetes-related foot disorders alone account for over \$10 billion annually in the United States, representing patient expenses for foot-related diseases. Scanning tools, including static foot scanners and force plates, are expensive, immobile, and unsuitable for continuous monitoring in natural environments. Furthermore, these methods often fail to provide actionable real-time data, delaying early interventions. Wearable devices, such as sensor-equipped insoles, address these challenges by enabling real-time monitoring of plantar pressure during activities like walking or running[6][7]. These systems, combined with advanced algorithms and data visualization tools, facilitate early detection of pressure imbalances and enable personalized healthcare solutions. The need for accessible, affordable, and accurate diagnostic tools to mitigate the impact of foot-related conditions highlights the importance of innovative systems like the one proposed in this study. By utilizing modular sensing technology and machine learning models, this research aims to bridge the gap in plantar pressure monitoring, offering an effective solution to improve diagnostics, rehabilitation, and overall foot health [8-12].

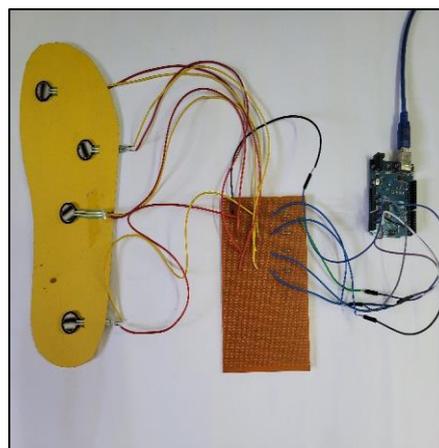
## 1.2 Proposed Objective

This research proposes a cost-effective and portable plantar pressure measurement system utilizing Force-Sensitive Resistors (FSRs) strategically placed to capture real-time pressure data from key foot regions. The system integrates an Arduino microcontroller for data acquisition and Python-based tools for data processing and visualization, including dynamic heatmaps. A machine learning model, specifically XGBoost, is employed for the accurate classification of foot conditions and detection of abnormal pressure patterns. The system's modular design ensures scalability and customization, enabling applications in rehabilitation, ergonomic footwear design, and preventive healthcare. By bridging accessibility with precision, the solution facilitates early diagnosis and actionable insights into foot health.

## 2. Methodology

### 2.1 Hardware Design

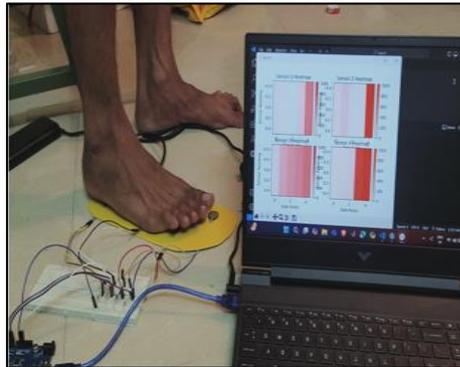
The proposed system utilizes Force-Sensitive Resistors (FSRs) strategically placed under key regions of the foot, including the toe, metatarsal, midfoot, and heel, to measure plantar pressure. An Arduino Uno microcontroller serves as the core processing unit, converting analog signals from the sensors into digital data for further processing. Direct wired connections (Figure 1.) between the sensors and the microcontroller ensure minimal signal interference and reliable data acquisition. The hardware design is compact and portable, making it suitable for real-world applications in clinical and non-clinical settings [5].



**Figure 1.** Hardware Design

## 2.2 Data Acquisition

The system collects real-time pressure data during activities such as walking or running. Each FSR undergoes calibration to establish its resistance-force relationship, ensuring accurate measurements. The data is transmitted through USB from the Arduino to a computer, where preprocessing tasks such as cleaning, normalization, and handling of missing values are performed. This preprocessing ensures the dataset is optimized for input into the classification algorithm.



**Figure 2.** Plantar Pressure Measurement and Analysis Setup

## 2.3 Classification Algorithm

To classify foot conditions and detect abnormalities, the system employs the XGBoost algorithm. This robust machine learning model analyses plantar pressure patterns and identifies specific conditions, such as flat feet or high arches in Figure 2. Feature selection focuses on critical pressure regions, enhancing the model's predictive accuracy. Hyperparameter optimization using GridSearchCV fine-tunes the model to achieve high classification performance and minimize errors.

**Table 1.** Classification based on Pressure Ranges

	Toe	Metatarsal	Midfoot	Heel
Flat Feet	Normal	Normal	High	High
High Arch	High	Low	Low	High
Normal Feet	Low	High	Normal	Normal

The classification of foot conditions based on plantar pressure distribution (Table 1) is applicable across all weight ranges, as it primarily compares pressure variations rather than absolute values. This method evaluates the relative pressure distribution across different foot regions, including the toe, metatarsal, midfoot, and heel, to determine foot type. For individuals with flat feet, the toe and metatarsal regions exhibit normal pressure, while the midfoot and heel experience high pressure. In contrast, those with a high arch show high pressure in the toe and heel, whereas the metatarsal and midfoot regions have low pressure. Individuals with normal feet demonstrate a low-pressure toe area, high metatarsal pressure, and normal pressure in both the midfoot and heel regions. Since this classification is based on relative pressure distribution rather than absolute values, it remains effective for individuals of all weight categories. This ensures accurate foot type identification and helps in developing orthopaedic solutions, custom footwear, and medical interventions for foot-related issues.

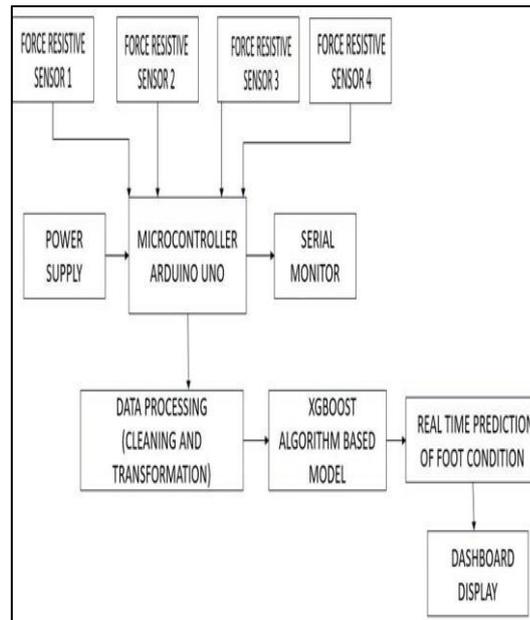
### **2.3.1 Model Training**

The XGBoost classifier is trained using processed plantar pressure data, with features representing key foot regions. Data is split into training (80%) and testing (20%) sets. Hyperparameter tuning through GridSearchCV optimizes model performance. Metrics such as accuracy, precision, and F1-score validate the model, while feature importance highlights critical pressure points for classification.

### **2.4 Dashboard Display**

An interactive dashboard, developed using Streamlit, provides a user-friendly interface for real-time visualization and analysis. Pressure data is displayed as heatmaps generated with Python's Seaborn library, offering intuitive insights into pressure distribution across the foot. The dashboard dynamically updates with user inputs and provides actionable insights, such as alerts for high-pressure zones and recommendations for improving foot health.

### 3. Block Diagram



**Figure 3.** Block Diagram of Proposed System

Figure 3 illustrates the block diagram of the proposed system for plantar pressure measurement and foot condition classification. The system comprises the following key components:

- **Force-Resistive Sensors (FSRs)**

Four FSRs are strategically placed to measure pressure at key foot regions, including the toe, metatarsal, midfoot, and heel. These sensors detect variations in pressure distribution during walking or standing, converting applied force into measurable resistance values.

- **Power Supply**

The sensors and microcontroller are powered by a stable DC supply, ensuring consistent performance and data accuracy during operation.

- **Microcontroller (Arduino UNO)**

The Arduino Uno serves as the central processing unit, acquiring analog signals from the FSRs and converting them into digital data for further processing. It ensures seamless communication between sensors and the processing system.

- **Serial Monitor**

The Arduino's serial monitor is used for real-time data visualization during initial testing and debugging, enabling validation of sensor outputs and system integrity.

- **Data Processing (Cleaning and Transformation)**

The acquired raw data undergoes preprocessing, including noise removal, normalization, and transformation. This ensures the data is clean and formatted for machine learning analysis, improving the accuracy of predictions.

- **XGBoost Algorithm-Based Model**

The pre-processed data is fed into an XGBoost-based classification model. This machine learning algorithm analyses the pressure patterns to classify foot conditions, such as normal, flat feet, or high arches.

- **Real-Time Prediction of Foot Condition**

The trained model provides real-time predictions of foot conditions, enabling immediate identification of pressure abnormalities and gait issues.

- **Dashboard Display**

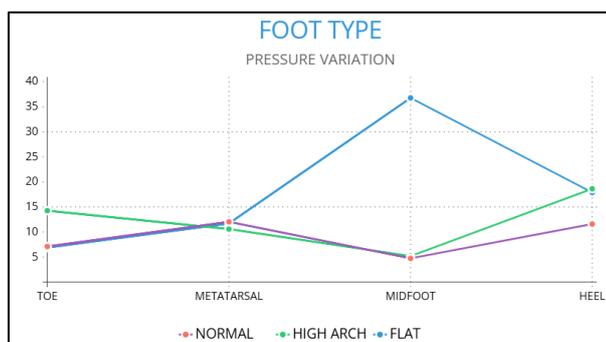
The interactive dashboard developed using Streamlit presents the results, including heatmaps of pressure distribution and condition classification. This user-friendly interface aids in easy interpretation of data and actionable insights for healthcare or performance optimization.

### **3.1 Software Design and Implementation**

The software for the modular piezoelectric sensing insole system is designed to process, analyze, and visualize plantar pressure data efficiently. It integrates real-time data acquisition, preprocessing, machine learning-based classification, and interactive visualization for foot health analysis.

The pressure data is collected in real-time using four force-sensitive resistors (FSRs) placed at key regions of the foot, including the toe, metatarsal, midfoot, and heel. An Arduino

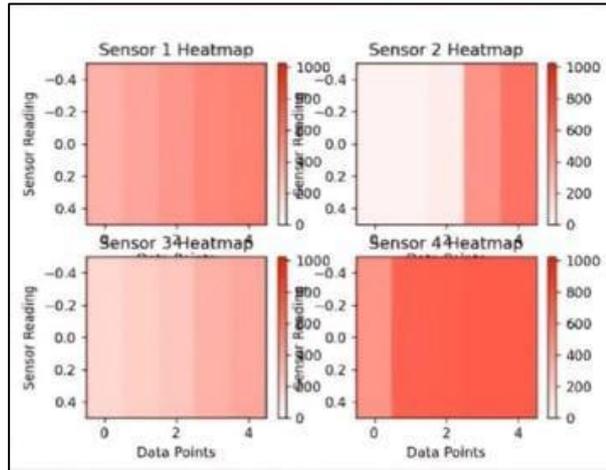
Uno microcontroller converts the analog signals from the sensors into digital data, which is sent to a Python-based system for further processing. The digital data undergoes several preprocessing steps, including cleaning, normalization, and feature extraction, to ensure consistency and accuracy. Cleaning involves removing noise using filtering techniques using NumPy, while normalization standardizes the pressure readings to a common scale using scikit-learn. Feature extraction focuses on selecting the most relevant information; in this case, the raw pressure values from each of the four FSRs are likely used directly as features. Missing or noisy data is handled, and pressure readings are standardized for machine learning compatibility. The XGBoost classifier is employed to detect foot conditions such as flat feet and high arches based on the processed pressure distribution (Table 1). The model, optimized using hyperparameter tuning with GridSearchCV from scikit-learn, achieves high accuracy in real-time predictions. The pressure variations are depicted in Figure 4



**Figure 4.** Pressure Variation

### 3.2 Heatmap Visualization

Pressure data is visualized (Figure 5) as heatmaps using Seaborn. A colour gradient, from white (low pressure) to red (high pressure), represents pressure intensity across different foot regions. These heatmaps dynamically update to highlight areas of concern, aiding in quick assessments.



**Figure 5.** Heatmap

## 4. Results and Discussion

### 4.1 Model Performance

The XGBoost classifier demonstrated high accuracy in predicting foot conditions based on plantar pressure data. The model achieved precision, recall, and F1-score metrics showing balanced performance across all classes. These results highlight the effectiveness of the model in detecting foot conditions such as flat feet, high arches, and normal feet. The model's ability to classify foot conditions even with overlapping pressure patterns showcases its robustness and suitability for real-world applications.

### 4.2 Dashboard Usability

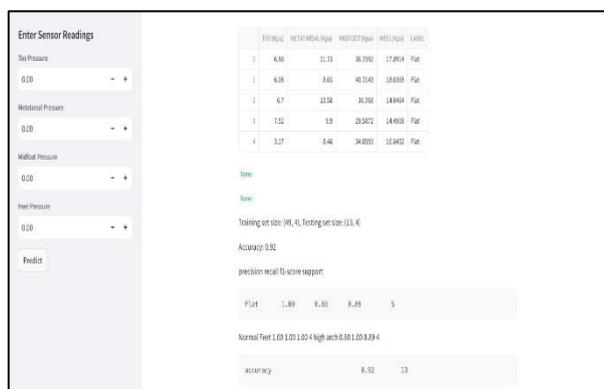
The interactive dashboard provided an easy-to-use interface for inputting pressure values and visualizing predictions. The system displayed classified foot conditions along with confidence scores, helping users understand the results. High-pressure zones were flagged with recommendations for corrective actions, such as using orthopaedic footwear or seeking medical attention. The streamlined user experience made the system accessible for both healthcare professionals and individuals.

### 4.3 Insights from Collected Data

Analysis of the collected dataset revealed distinct pressure distribution patterns across different foot conditions:

- Normal Feet: Pressure is evenly distributed between the heel, midfoot, and toes.
- Flat Feet: Increased pressure in the midfoot region due to collapsed arches.
- High Arches: Concentrated pressure in the heel and metatarsal regions, indicating reduced ground contact.

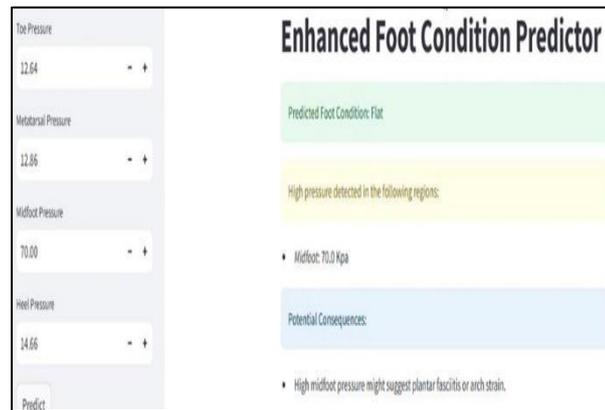
The pressure variation across different foot regions, toe, metatarsal, midfoot, and heel, plays an important role in understanding foot biomechanics and detecting potential medical conditions. High toe pressure may indicate a risk of bunions or hammertoe, while elevated metatarsal pressure can lead to metatarsalgia or stress fractures. Similarly, high midfoot pressure might suggest plantar fasciitis or arch strain, whereas excessive heel pressure could indicate a risk of heel spurs or Achilles tendinitis. To enhance the accuracy of plantar pressure analysis, the XGBoost (Extreme Gradient Boosting) algorithm is employed. XGBoost is a powerful machine learning model that efficiently processes structured data, identifies pressure distribution patterns, and predicts abnormalities with high accuracy and robustness. This approach aids in early diagnosis of foot-related conditions, orthopaedic assessments, and personalized treatment recommendations, ensuring better foot health management.



**Figure 6.** Result and Observation

Figure 6 illustrates the user interface of the developed plantar pressure classification system, which takes sensor inputs for toe, metatarsal, midfoot, and heel pressure. The system processes these values and classifies the foot type accordingly. The table on the right side displays sample sensor readings along with their corresponding labels, indicating classification results. The model was trained using a dataset split into a training set of 49 samples and a testing set of 13 samples. The achieved accuracy of the model is 92%, demonstrating its effectiveness in classifying foot types.

Additionally, performance metrics such as precision, recall, and F1-score are presented for different foot conditions, including Flat Feet, Normal Feet, and High Arch. The classification report shows that the model performs well across all categories, achieving an F1-score of 0.89 for Flat Feet, 1.00 for Normal Feet, and 0.89 for High Arch.



**Figure 7.** Foot Condition Detector

Figure 7 has successfully captured real-time plantar pressure data using multiple sensors. The graphical representation on the laptop displays pressure variations across different foot regions. The XGBoost algorithm effectively analysed the data, identifying distinct pressure patterns. This approach enables accurate foot condition assessment, making it useful for medical diagnostics and orthopaedic applications. These patterns provide valuable insights for designing personalized interventions, including footwear and rehabilitation programs. The developed system demonstrates strong potential for clinical and personal health applications. Its cost-effective design and portability make it suitable for widespread adoption in diagnosing and monitoring foot health. By enabling early detection of foot conditions, the system can help reduce the risk of complications, improve mobility, and enhance overall quality of life.

## 5. Conclusion

The results obtained from this research demonstrate the efficacy of the proposed plantar pressure analysis system in accurately measuring and analysing foot pressure data. The system's real-time data acquisition and visualization capabilities, including the dynamic heatmap representation, effectively highlight variations in pressure intensity across critical regions of the foot. These visual and analytical tools enable precise identification of high-pressure zones, which are important for diagnosing foot-related health issues such as plantar

fasciitis, bunions, and metatarsalgia. The performance metrics of the XGBoost classifier, with optimized hyperparameters, further emphasize the robustness and reliability of the predictive model in classifying foot conditions based on plantar pressure data. The comprehensive insights derived from the system not only validate its functionality but also establish a strong foundation for future applications in clinical diagnostics, rehabilitation, and personalized footwear design. By combining accurate measurements, advanced machine learning models, and user-friendly interfaces, the results demonstrate the system's potential to significantly improve foot health monitoring and preventive care.

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