Smart Shoe Insole with Flexible Pressure and Temperature Sensor Mechanism for Environmental Adaptation and Reliability

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***Abstract*— Individuals experiencing gait disfunction such as the elderly those with peripheral nervous system damage or individuals with Parkinson's disease face a heightened risk of physical injury due to imbalanced weight distribution. Despite recent advancements in wearable movement trackers, there remains a significant need for a reliable long term plantar pressure monitoring system. While some existing devices measure pressure characteristics many are hindered by limitations in spatial resolution, sensitivity and the presence of bulky peripherals. Here we introduce a flexible smart insole system that integrates screen printed nanomaterials to create a high density piezoresistive sensor array enabling accurate plantar pressure measurement during daily activities. To ensure scalable and cost-effective manufacturing we utilize a screen-printing method to fabricate 173 carbon-based sensors directly onto a flexible insole circuit. The printed sensors demonstrate a remarkable sensitivity of −0.322 kPa–1, surpassing previous benchmarks. When combined with a wearable mobile communication circuit this system offers a comprehensive analysis of the user's plantar pressure distribution. Experimental studies conducted with human subjects showcase the smart insole's real-time monitoring capabilities in common daily ambulation scenarios. The integration of high spatial resolution, exceptional sensitivity and a fully mobile wearable system holds significant promise for enhancing outcomes across various applications from healthcare to athletics.**

I. Introduction

Smart wearable technologies have gained increasing attention in recent years due to their ability to monitor human activity, health status and environmental conditions in real time. Among these smart shoe insoles equipped with flexible pressure and temperature sensors present an efficient solution for continuous gait analysis posture monitoring and adaptive environmental interaction. The integration of flexible sensors enables precise detection of plantar pressure distribution and temperature variations ensuring both comfort and safety for the user This study focuses on the design and development of a smart shoe insole that incorporates flexible pressure and temperature sensors optimized for environmental adaptation and reliability. The system utilizes advanced materials and fabrication techniques such as additive manufacturing to achieve high sensitivity and mechanical durability. Furthermore, embedded processing units and data acquisition modules allow real-time analysis and wireless transmission of sensor data. Such an adaptive system holds significant potential for applications in sports performance monitoring, rehabilitation and preventive healthcare offering an intelligent interface between human physiology and ambient conditions.

II. Methods

A. User Interface and Accessibility

A user-centered design (UCD) approach enhances interface simplicity and accessibility. Clear data visualization tool such as pressure heatmaps and simplified gait graphs make results understandable without expert interpretation. Customizable alerts, larger fonts and voice feedback greatly improve usability for elderly and visually impaired users. Streamlined navigation allows users to access information or adjust settings within minimal steps reducing cognitive effort and task completion time.

B. Integration and Feedback Mechanism

The insole system's ease of use is strengthened by seamless integration with mobile and web applications via Bluetooth or Wi-Fi. Real-time pressure thresholds and alerts offer immediate corrective feedback to the wearer helping prevent overloading and potential injury. The dual-interface design for patients and physicians further simplifies data handling during rehabilitation and monitoring ensuring efficient communication and analysis.

III. Testing and Validation Process

Insole Calibration

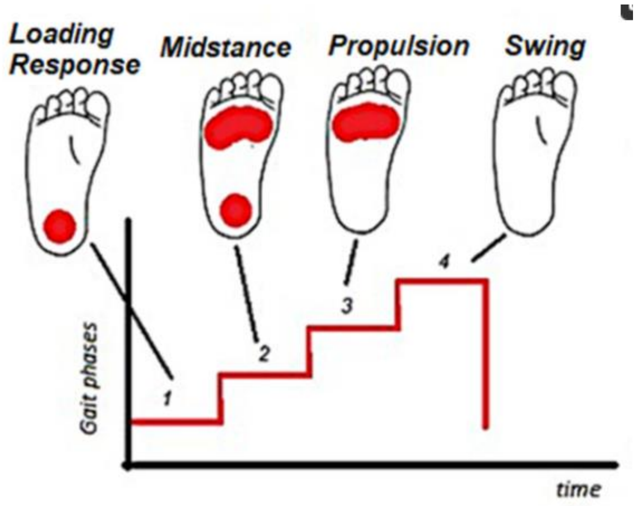


Figure 1. Walking phase identification based on activation sensor sequence. "Loading response" is based on calcaneus activation, "midstance" is based on calcaneus, lateral forefoot (5th metatarsal head), central forefoot (between the 2nd and 3rd metatarsals heads), and calcaneus activation, "Propulsion" is based on lateral forefoot (5th metatarsal head) and central forefoot (between the 2nd and 3rd metatarsals heads) activation, and "Swing" is based on no activation.

A. Insole Construction

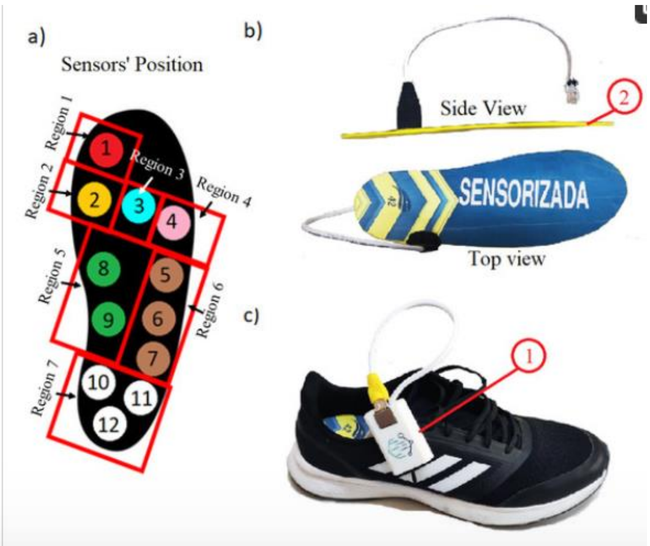


Figure 2. Visualization of the seven regions of sensors with 12 sensors in total. Visualization of the finished sensorized insole. The picture also shows the EVA base of the insole .Visualizing the compact sender device that connects with a sensorized insole using an RJ45 connector

B. Testing and Validation Process

After the calibration and signing of a free and informed consent form, each participant wore a pair of insoles and walked on the treadmill at a self-selected speed for 60 s to get used to the insole and then added 60 s for data collection.

The validity analysis was performed empirically by performing a concurrent validity analysis, in which the result of a developed instrument is compared with a "gold standard". In this way, the sensor insoles force estimations were compared against those from a double-belted instrumented treadmill containing two force plates (TFP) and a walking surface of 1.75 × 1 m at 1000 Hz, Corp, Columbus, OH, USA to verify the validation of the insoles' sensors. However, is no consensus in the literature regarding the calculation of validity. The Pearson coefficient is one of the most used coefficients and can be complemented with the coefficient of multiple correlations (CMC). According to correlation values above 0.7 are considered high correlation and, in this study, were the minimum value necessary for validation. For the validity calculation, 30 steps from all recorded steps were considered (selected by the central part, excluding the extremes), and arithmetic mean was performed to obtain a single mean step representing the volunteer's gait. The average curves were synchronized starting based on the initial contact phase of the gait and the acquisition frequency of the instrumented treadmill (force plate) was adjusted to the same as the senso insole. The raw data was filtered with a 4th order low pass Butterworth filter with a cut-off at 6 Hz for the kinematic data.

C. Equations

$$COP_x(t) = \frac{\sum_{i=1}^{i=7} X_i Px_i}{\sum_{i=1}^{i=7} X_i}$$

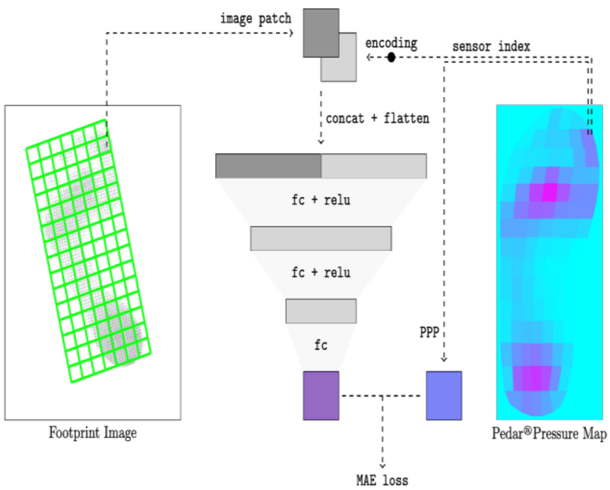
(1)

$$COP_y(t) = \frac{\sum_{i=1}^{i=7} X_i Py_i}{\sum_{i=1}^{i=7} X_i}$$

D. Classification and Regression Trees (CART)

The IA grouped the samples with similar curve shape (based on the frequency spectrum) adding to the database new information: group classification number. After grouping an investigative process was start identify common characteristics that may facilitate the clinical interpretation of possible relevant issues of each group(Data Mining).In other words a set of bio indicators used in pronation studies involving GRF was calculated of each walking phase which are: mean force[62]mid lateral centre of pressure access [63],time duration percentage[63].The bio indicators were extracted from the same database and were used to predict for the training of CART algorithm. They were statistically validated with TFP using a sample result indicated no significant difference between SI and TFP. In this process the CART was not used to predict the result but to find the bio indicator's cut off points to define a specific group. Mean force was calculated as a arithmetic average of vGRF registered, while impulse was the product of force by time on each walking phase. During walking the impulse related to force absorption. The centre of pressure was the GRF's virtual mean position acting on the foot's sole. It generally starts slightly away from the posterior end of the calcaneus and travel on the foot's soles during the stance phase towards the second metatarsal head.

IV. Flowchart



The User Interface (UI) Module in a smart shoe insole system acts as the communication bridge between the user and the embedded sensing hardware. The theory behind this module is grounded in human–computer interaction (HCI), where complex sensor data is transformed into meaningful, easy-to-understand visual information. This module is responsible for collecting the processed output sent by the microcontroller—such as pressure distribution values, temperature readings, gait patterns, and alerts—and presenting them through an intuitive graphical interface on a mobile device or monitoring application.

The UI module typically uses Bluetooth Low Energy (BLE) to receive real-time data from the insole, which is then displayed using interactive charts, color-coded pressure maps, temperature indicators, and notifications. Theoretical principles such as usability, clarity, minimal cognitive load, and responsiveness guide the design of this interface. The goal is to ensure that the user can quickly interpret foot conditions without technical expertise. For example, high-pressure zones may be represented in red, while normal zones appear in green; similarly, temperature warnings may trigger pop-up alerts or vibration notifications.

A. ***System design***

[Start]
↓
[Sensor Activation]
↓
[Data Acquisition]
↓
[Signal Processing]
↓
[Data Analysis]
↓
[Communication Module]
↓
[User Interface]
↓
[Feedback/Action]
↓
[Loop back to Data Acquisition]

B. ***Modules***

DS18B20 temperature sensor is used to accurately measure the foot's temperature and detect any abnormal thermal changes that may indicate inflammation, infection, or poor circulation. The sensor provides precise digital temperature readings using its 1-Wire communication interface, allowing easy integration with the microcontroller and reducing wiring complexity. Its high accuracy, fast response, and ability to operate reliably in varying environmental conditions make it suitable for continuous monitoring inside the insole. The temperature data captured by the DS18B20 is processed and transmitted for further analysis, enabling real-time foot-health monitoring and early detection of potential issues.

The proposed smart insole system offers several significant advantages that make it more effective, practical, and reliable compared to existing solutions. Its dual-sensor integration, combining both pressure and temperature sensing, enhances measurement reliability and provides a more comprehensive analysis of foot conditions. The system's lightweight and flexible design ensures user comfort, making it suitable for continuous daily wear without causing discomfort or movement restrictions. With real-time wireless communication, users can conveniently access live data, track foot health, and receive updates without physical connections or delays. The system also demonstrates high adaptability to environmental changes, ensuring consistent accuracy even under varying humidity, sweat, or temperature conditions. Furthermore, it achieves a low-cost yet efficient implementation, making it accessible for research, clinical use, and personal monitoring without compromising performance.

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