

Development of Fiber-Optic Based Pressure Sensor Insole System for Gait Analysis

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Abstract

This project addresses the important need for precise and accessible gait subphase detection and dynamic balance evaluation methodologies, particularly for those with neurological illnesses and mobility limitations. The current gait analysis tool landscape provides hurdles, with older approaches being expensive and limited, and wearable sensors having constraints such as high costs and the requirement for recalibration. In response, the goal of this study is to create a Balance Assessment Through Fiber Optic-Based Pressure Sensor Insole Development for Gait Analysis, that reliably evaluates gait subphases and quantifies dynamic balance during human locomotion. Using plastic optical fibre (POF) technology, six fibre optic pressure sensors are embedded at crucial points on the insole. For real-time signal processing and analysis, the sensors are integrated with a data collecting system comprised of Arduino, NodeMCU, and MATLAB. The prototype testing results show consistent voltage outputs in the hindfoot area, averaging 0.06V, and in the forefoot area, averaging 0.10V. These results demonstrate the system's capability to detect pressure changes accurately. These results not only validate the efficacy of the developed technology but also pave the way for enhanced understanding of gait dynamics, potentially leading to improved rehabilitation strategies and assistive technologies tailored to individual gait patterns and balance needs. The project's findings will improve understanding of gait dynamics, opening the path for better rehabilitation programs and assistive technologies.

1. Introduction

Learning about and measuring human gait, particularly its impact on balance, is essential for the rehabilitation of patients with neurological illnesses and mobility difficulties [1-2]. Accurate gait analysis helps in diagnosing and treating various conditions, improving patients' quality of life and aiding in their recovery. As wearable assistive devices like ankle orthoses and exoskeletons become more prevalent, accurate detection of gait subphases becomes critical for effective device control [1-2]. Proper detection ensures these devices can adjust in real-time to the user's movements, providing better support and enhancing mobility.

Traditional gait analysis techniques, such as force platforms and motion capture, are accurate but limited [5]. These systems provide detailed data but are often restricted to clinical settings due to their high costs, bulkiness, and the need for specialized environments, making continuous and real-world monitoring impractical. They also require skilled technicians to operate, which further limits their accessibility and frequency of use. Wearable sensors such as ultrasonic, EMG, footswitches, and inertial sensors are becoming increasingly popular, although they are expensive and require calibration [4]. Foot pressure insoles have shown

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promise, but their effectiveness depends on precise placement. Fiber optic sensors are desirable for gait analysis because of their high sensitivity, resolution, and dynamic range [3]. In contrast, current applications highlight calibration difficulties.

The development of wearable systems for human gait analysis has seen significant advancements in recent years, driven by the need for precise and real-time data to improve healthcare outcomes. A wearable system based on plantar pressure sensors has been developed that demonstrated promising results in accurately capturing gait patterns and offering valuable insights into the biomechanics of walking [6]. This technology leverages the integration of sensors into wearable devices, providing a non-invasive and efficient means of monitoring gait, which is crucial for the early detection and management of various health conditions.

One notable technology in gait analysis is the Kinect sensor, which has been evaluated for its validity in assessing gait. A focused review has been conducted on the use of Kinect for gait assessment, highlighting its potential as a cost-effective and accessible tool for capturing gait parameters [7]. Despite some limitations in accuracy compared to traditional gait analysis methods, the Kinect sensor offers a valuable alternative for clinical and home-based applications, facilitating wider accessibility to gait analysis for diverse populations.

The incorporation of Internet of Things (IoT) technology has further enhanced the capabilities of gait detection systems. A wireless IoT system has been explored that utilizes force-sensitive resistor (FSR) sensors and wearable devices to detect gait patterns [8]. This system underscores the potential of IoT in creating intelligent and connected healthcare solutions, enabling continuous and remote monitoring of gait. Such advancements are instrumental in providing timely interventions and personalized care for patients with gait abnormalities.

The theoretical frameworks and methodologies in gait analysis have been extensively documented in the literature. A comprehensive overview of various methods has been proposed in gait analysis, detailing the evolution of techniques and their applications in clinical settings [9]. Furthermore, a theoretical framework for understanding gait variability is offered, emphasizing its importance in biomechanics and gait analysis [10]. These foundational works contribute to the ongoing development and refinement of gait analysis technologies, supporting the integration of innovative approaches in enhancing gait assessment and treatment strategies.

The purpose of this project is to address these challenges by developing a fibre optic-based insole system for accurate gait subphase recognition and balance assessment. This system aims to offer a comprehensive solution that combines the high sensitivity and resolution of fiber optic sensors with the portability and ease of use required for real-world applications. The project involves embedding six fiber optic pressure sensors at crucial points on the insole, connected to an Arduino and NodeMCU for real-time data processing and analysis using MATLAB. This setup aims to offer a portable, accurate, and user-friendly solution for gait analysis, capable of providing detailed insights into foot pressure distribution and gait patterns. This strategy has the potential to increase the efficacy of gait therapy, particularly for those with mobility difficulties. The study's relevance stems from its contribution to the progress of gait analysis and wearable healthcare technologies, both of which will ultimately improve the well-being of people suffering from gait-related disorders. By providing a more accessible and precise method for gait analysis, this project supports advancements in personalized healthcare and rehabilitation, offering significant benefits to patients and healthcare providers alike.

2. Methodology

This section discusses the hardware configuration as well as the fibre optic-based insole system that is utilised to precisely monitor gait dynamics.

2.1 Hardware Design

Fig. 1(a) depicts the circuit design, which connects six fiber optic sensors to the microcontroller. Fig. 1(b) shows the completed project assembly, which incorporates all components, including the Arduino and NodeMCU. It also shows how the project's hardware configuration is intended to accurately and seamlessly monitor gait dynamics. Each of the six plastic optical fibers is housed in a clear tube within the insole. These tubes, strategically arranged throughout the insole, serve as conduits, carrying light from the red laser diodes to photodiodes at the opposite ends of the fibers. When pressure is applied to the insole when walking or running, both ends of the optical fibers are pulled together, producing a connection that permits light to be sent from laser diodes to photodiodes.

This technology senses light intensity variations caused by foot pressure and movement. The electrical impulses generated by the photodiodes are then sent to the NodeMCU ESP32, which wirelessly sends data to the Arduino Uno microcontroller. It allows for real-time monitoring and analysis of gait patterns, with applications spanning from healthcare to biomechanics research and athletic performance optimization.

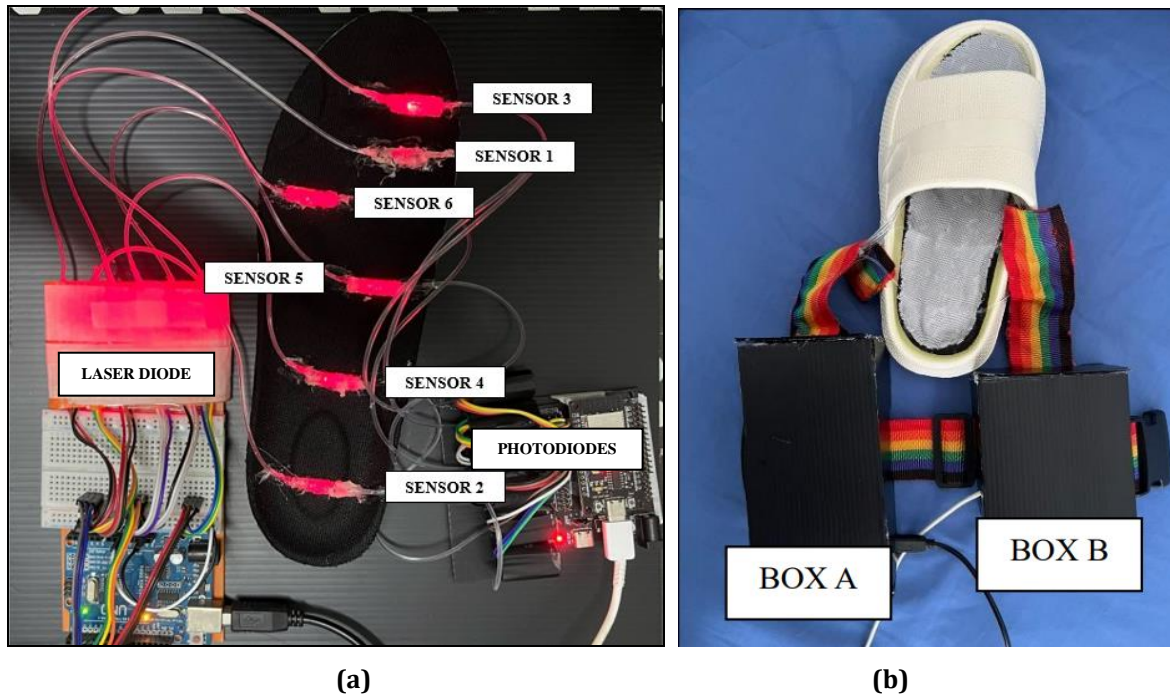


Fig. 1 (a) *Hardware Circuit Design* and (b) *Final Project Assembly*

2.2 Fiber Optic Based Insole System

As shown in Fig 2, the proposed system would provide an innovative tool for monitoring the development of a fiber optic-based insole system for gait analysis. Six fibre optic pressure sensors will be carefully placed at pressure sites throughout the insole. Each sensor is made up of a plastic optical fibre (POF) embedded in the insole, a flexible tube that acts as a bridge between the POF and the sensor body, and a plastic POF with a red laser diode serving as a light source.

The laser diode sends light to a fibre-based photodiode receiver, which detects the strength of the reflected light. This mechanism measures pressure variations across the insole when moving. The Arduino then monitors the output voltage from each photodiode receiver connected to the fiber optic sensors. The voltage data from the Arduino is received by the NodeMCU, which serves as a middleman. It converts this data into pressure measurements by applying a sensor calibration equation. Following that, the NodeMCU creates a data packet including timestamped pressure readings from all sensors.

The pressure data is retrieved for analysis using the MATLAB software. The MATLAB algorithms then calculate the pressure distribution throughout the insole surface for each step taken by the user. Based on pressure distribution patterns and temporal fluctuations, the system uses complex algorithms to recognize and segment gait subphases such heel strike, stance, and toe-off.

Fig. 3 shows the flowchart of the project that provides a visual representation of the entire process, from initial design to final implementation. It outlines each step in the development of the Fiber Optic-Based Pressure Sensor Insole System for Gait Analysis, including sensor placement, data acquisition, signal processing, and data analysis.

Fig. 4 shows how the project's circuit diagram was designed. The following components were used in this hardware circuit: Plastic Optical Fiber, Red Laser Diode, Arduino Uno, TEMA6000 Light Sensor Module, and NodeMCU ESP32.

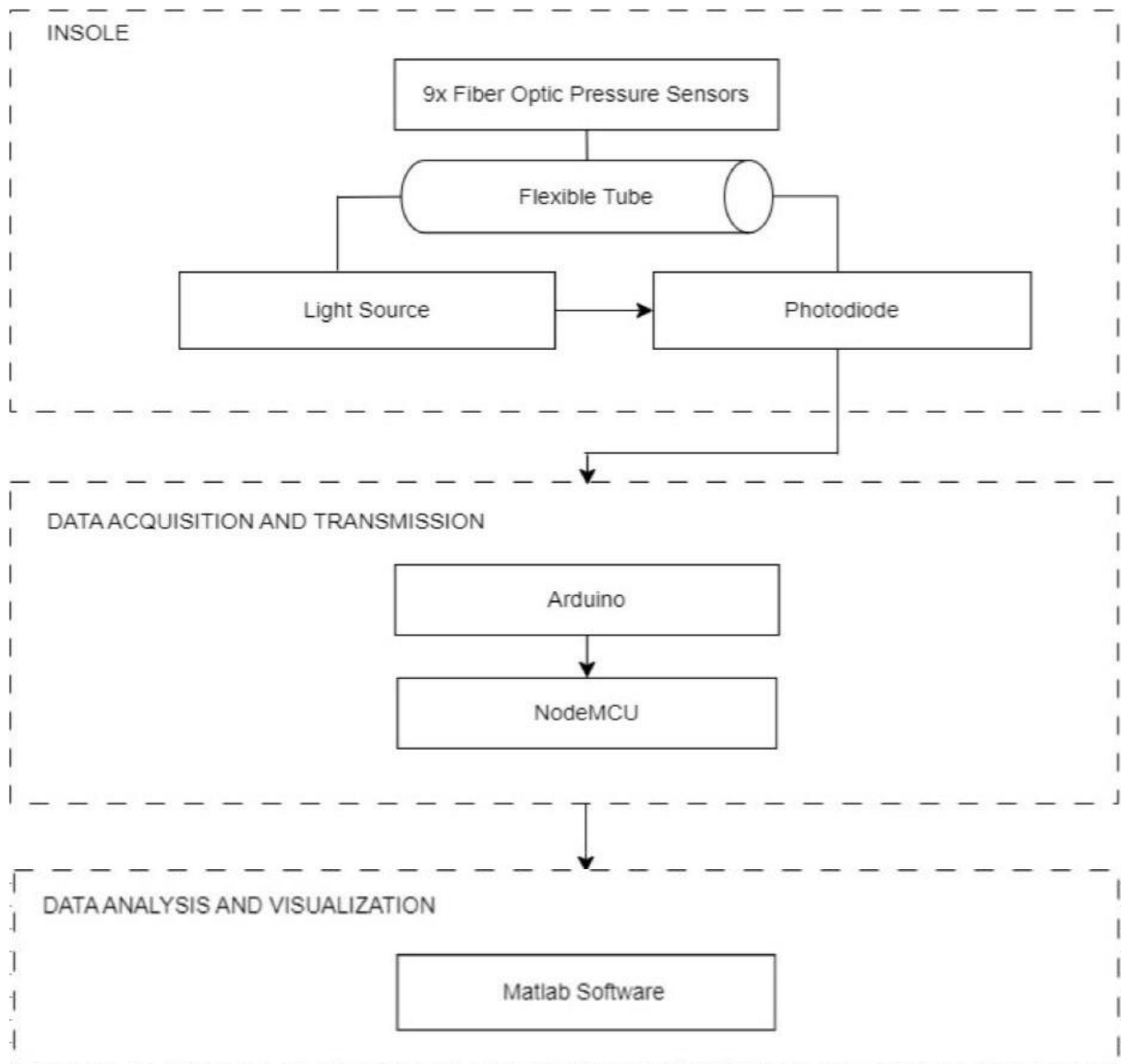


Fig. 2 Block Diagram of the Project.

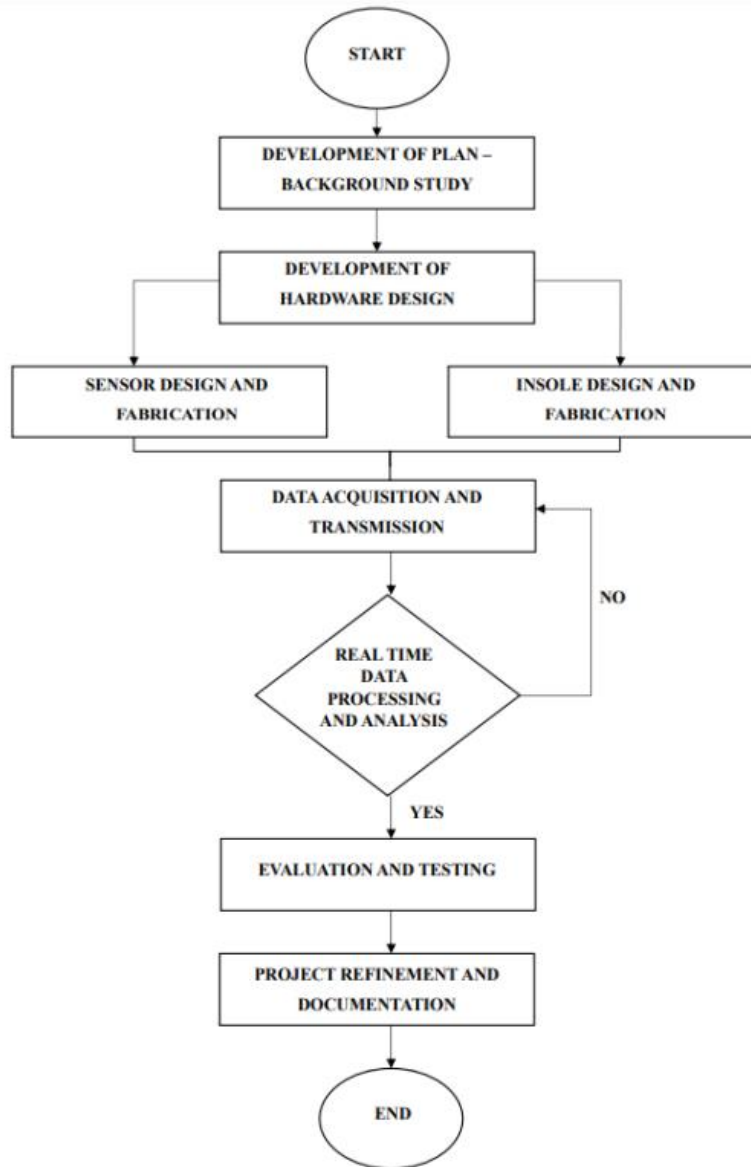


Fig. 3 Flowchart of the Project.

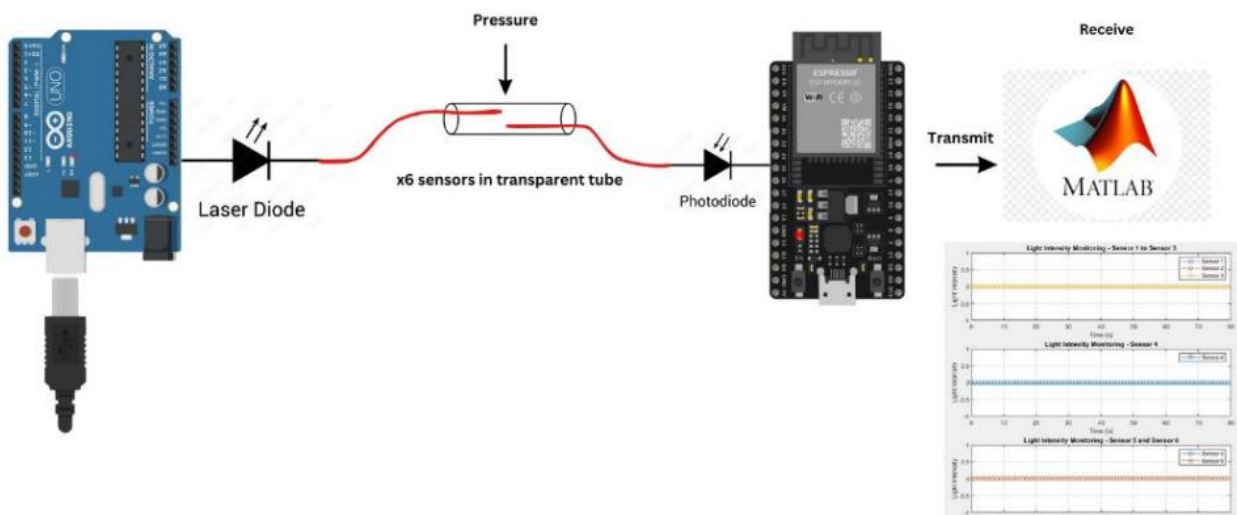
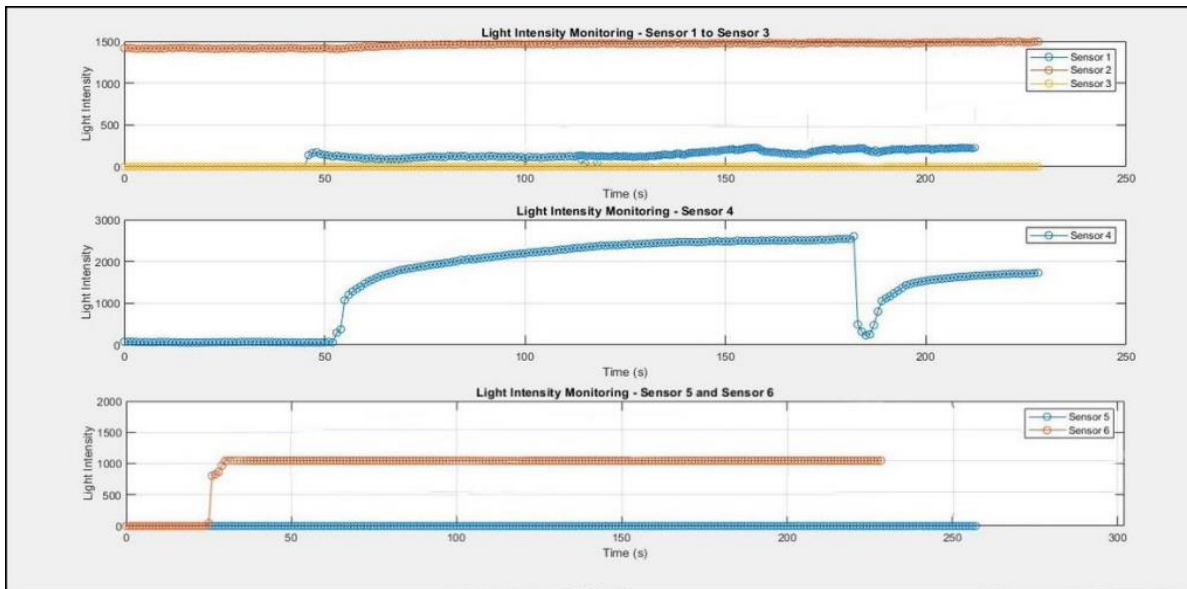


Fig. 4 Circuit diagram of the project.

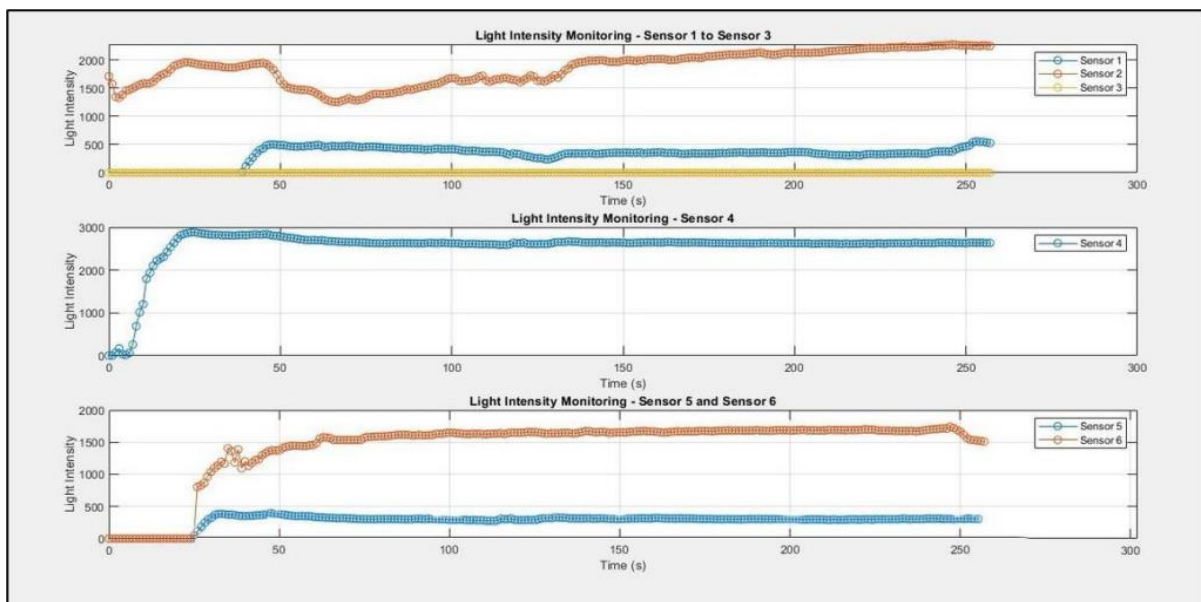
3. Results and Discussion

Two volunteers were selected to test the insole system's performance and reliability through two tasks: standing still for one minute and walking 5 meters and. These tasks simulated everyday movements, allowing for a comprehensive assessment of the insole's ability to gather and evaluate foot pressure data in both dynamic and static contexts. Each volunteer wore slip-on sandals with the project's footbed, and hardware components were securely attached to their ankle, powered by a portable 10,000mAh power bank for stability and ease of movement during the experiments.

For the standing test, volunteers stood still for one minute to assess the insole's capability to accurately measure and maintain pressure readings under static conditions, ensuring sensor stability and reliability after inactivity. The result for the standing test is shown in Fig. 6 where Fig. 6(a) depicts data from Volunteer 1, demonstrating significant pressure fluctuation in both the forefoot and hindfoot. Fig. 6(b) depicts Volunteer 2's data, which show minimal midfoot pressure. Pressure readings from standing were evaluated to determine the insole's effectiveness in capturing real-time pressure data during static pressures.



(a)



(b)

Fig. 6 (a) Data from volunteer 1 and (b) Data from volunteer 2.

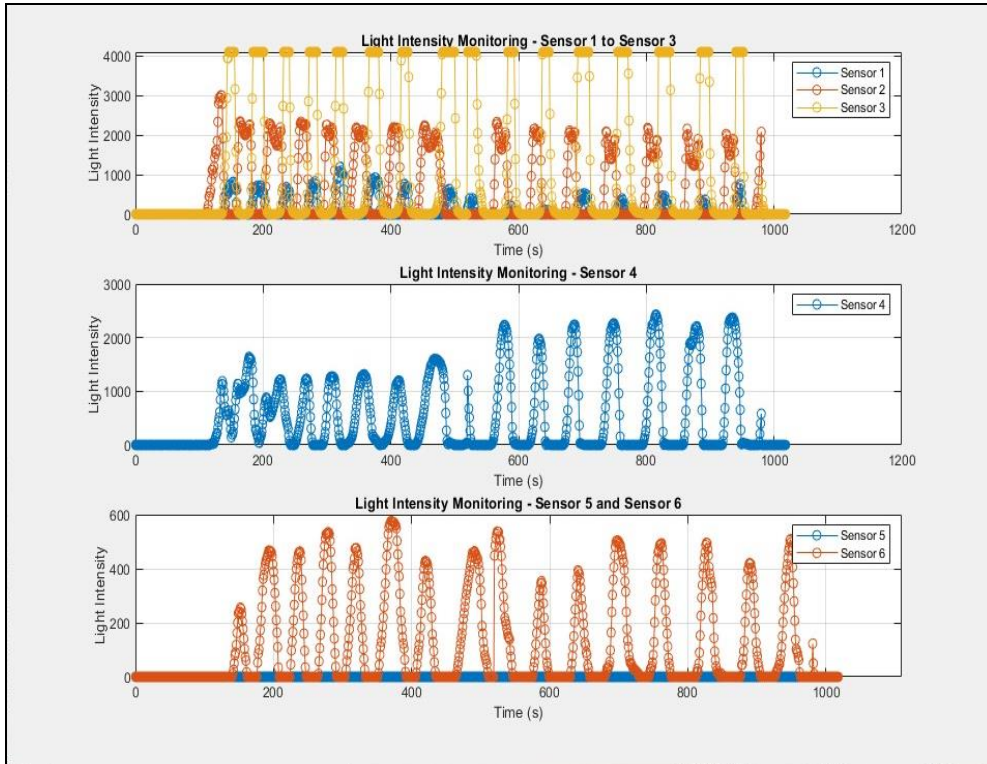
Table 1 provides a comparative analysis of the standing test data between Volunteer 1 and Volunteer 2. This table highlights differences in pressure distribution patterns and overall stability, offering insights into individual variations in balance and posture.

Table 1 Data Comparison for Volunteer 1 and 2 for Standing Test.

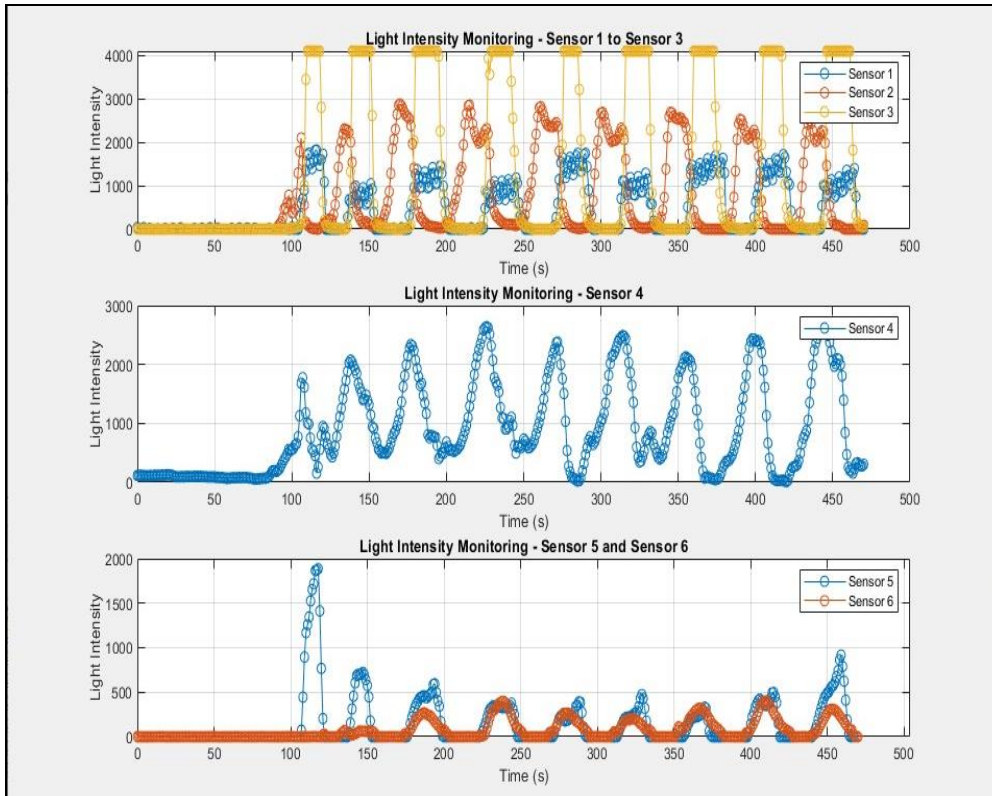
Sensor Region	Volunteer 1 – Pressure (Light Intensity)	Volunteer 2 – Pressure (Light Intensity)	Conclusion – Volunteer 1	Conclusion – Volunteer 2
Forefoot (Sensors 1, 3, 6)	Sensor 1: Low Sensor 3: No data Sensor 6: Moderate-High	Sensor 1: Low Sensor 3: No data Sensor 6: Moderate-High	Substantial weight distribution. Sensor 1: Minimal pressure levels Sensor 3: No pressure Sensor 6: Varying pressure levels	Substantial weight distribution. Sensor 1: Minimal pressure levels Sensor 3: No pressure Sensor 6: Varying pressure levels
Midfoot (Sensor 5)	No Data	Low, stable readings	No pressure indicating normal arch	Minimal pressure indicating no arch
Hindfoot (Sensors 2, 4)	Sensor 2: High Sensor 4: High, with a brief dip	Sensor 2: Moderate-High Sensor 4: High, stable	Sensor 2: High pressure levels Sensor 4: High pressure levels	Sensor 2: Varying pressure levels Sensor 4: High pressure levels

The standing test results revealed distinct pressure distribution patterns between the two volunteers. Volunteer 1 exhibited high pressure on the hindfoot and moderate to high pressure on the forefoot, suggesting a more typical pressure distribution. However, the data from sensor 4 indicated subtle weight shifts, particularly in the hindfoot area. In contrast, volunteer 2 showed low light intensity and pressure readings in the midfoot region, indicating insufficient arch support and a tendency towards flat foot.

For the walking test, volunteers were asked to walk at their own pace, enabling the sensors to capture pressure changes and evaluate the system's responsiveness and accuracy in detecting gait patterns and pressure distribution. Fig.7 shows the result for the walking test where Fig. 7(a) depicts data from Volunteer 1, demonstrating no pressure in the midfoot, indicating a normal arch foot. Fig. 7(b) depicts Volunteer 2's data, which show minimal midfoot pressure, indicating flatfoot.



(a)



(b)

Fig. 7 (a) Data from Volunteer 1 and (b) Data from Volunteer 2

Table 2 summarizes and compares the walking test data for both volunteers, providing insights into variations and similarities in their gait dynamics and balance assessment.

Table 2 Data Comparison for Subject 1 and 2 for Walking Test.

Sensor Region	Volunteer 1 – Pressure (Light Intensity)	Volunteer 2 – Pressure (Light Intensity)	Conclusion – Volunteer 1	Conclusion – Volunteer 2
Forefoot (Sensors 1, 3, 6)	Sensor 1: Consistent Low Sensor 3: High Sensor 6: High	Sensor 1: Moderate Sensor 3: High Sensor 6: Low	Substantial weight distribution. Sensor 1: Low pressure levels Sensor 3: High pressure levels Sensor 6: High pressure levels	Substantial weight distribution. Sensor 1: Moderate pressure levels Sensor 3: High Pressure levels Sensor 6: Low pressure levels
Midfoot (Sensor 5)	No reading	Low-Moderate reading	No pressure	Minimal pressure levels
Hindfoot (Sensors 2, 4)	Sensor 2: Moderate Sensor 4: Moderate-High	Sensor 2: Moderate Sensor 4: High	Sensor 2: Moderate pressure levels Sensor 4: High pressure levels	Sensor 2: Moderate pressure levels Sensor 4: High pressure levels

The walking test results highlighted different pressure distribution patterns between the two volunteers. Volunteer 1 demonstrated moderate to high pressure on the hindfoot, significant variance in the forefoot, and no pressure data for the midfoot, indicating a regular pressure distribution and likely normal foot arch due to the consistent pressure in the forefoot and hindfoot regions. Conversely, Volunteer 2 exhibited minimal pressure in the midfoot area, indicating a lack of arch support and flat foot. The moderate to high pressure in the hindfoot and varying pressure in the forefoot further underscored the distinct weight distribution associated with flat foot.

4. Conclusion

The Fiber-Optic Based Pressure Sensor Insole System for Gait Analysis project successfully achieved its objectives through comprehensive development, calibration, and testing phases. Its primary goal was realized by embedding six plastic optical fibers within an insole, each equipped with a red laser diode and TEMT6000 Light Sensor Module to detect pressure changes during human locomotion. This configuration enabled precise measurement of foot pressure distribution and gait subphases. The project also utilized an Arduino microcontroller and NodeMCU ESP32 for real-time data transmission to a computer, facilitating continuous monitoring of gait metrics wirelessly. Powered by a 5V portable battery bank, the system ensured uninterrupted operation. Calibration using a sphygmomanometer validated the relationship between pressure applied and light intensity data, crucial for accurate balance assessment during human subject testing. Matlab software processed the collected data, offering insights into foot pressure distribution and gait characteristics. Overall, the project demonstrated the feasibility of using fiber optic sensors for advanced gait analysis and holds promise for future applications in health monitoring and technology development.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

This author confirms sole responsibility for the following: planning and designing the study, data collection, analysis and interpretation of the outcomes, and paper writing.

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