An Intelligent Digital System For Foot-Weight Distribution Analysis

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***Abstract*— Maintaining proper weight distribution on the feet during daily activities can reduce postural and ambulatory issues. Therefore, accurate foot weight distribution analysis is crucial for medical science, occupational rehabilitation, physical therapy, sports, military training, and daily life postural training, influencing diagnostic and preventive healthcare. Despite the growing significance of body weight analysis, existing research in this domain is limited. The complexity of this issue arises from inherent variations in factors such as weight, height, Body Mass Index (BMI), physiological parameters, and accidentally conceived abnormalities. This paper introduces a novel approach to address this challenge by developing a smart digital system designed to analyze human body weight distribution across different parts of the foot. The system uses a data acquisition module connected with Force Sensing Resistor (FSR)-based matrix sensors placed under the plantar surface of the foot. The collected data is processed by an embedded system that uses analytic techniques to identify foot patterns and diagnose defects in the body. The proposed foot weight distribution system can be a helpful diagnostic tool for analyzing foot pressure distribution to identify and suggest potential medical problems (such as osteoporosis and prostheses). To validate the effectiveness of the system, a study involving 200 participants (comprising 100 males and 100 females) was conducted. The results show a significant level of accuracy in identifying abnormalities in osteoporosis and detecting prosthetic misalignment.**

***Index Terms*—Foot Analytics, Biomedical Engineering, Embedded System, Gait Analytics**

I. Introduction

Gait analysis and correct weight distribution on feet are emerging concepts in medical science. They are used for sport-related applications, balance control, footwear design, posture correction, and physical and occupational rehabilitation. While we stand or walk, our feet provide us balance and propulsion. Both feet work in collaboration with each other. Body distributes weight on different parts of the foot as it lands on the ground, rests and leaves the ground while standing, walking, and running.

As a reaction to our weight acting on the ground, some reactive forces, called ground reaction forces, act on our body [1]. These ground reaction forces are equal in magnitude and act in the opposite direction to the weight. Improper weight distribution during our daily lives can cause the ground reaction forces to act negatively on our body, leading to walking disorders, muscular pain, and even fractures [2].

Therefore, understanding weight distribution in daily life is a significant concern. Various devices are available in the market for weight distribution and plantar pressure measurement. Platform systems and in-shoe systems are commonly used in rehabilitation centers and research [3]. These devices use sensors [4], [5] for detecting weight or pressure distribution, such as piezoelectric, piezoresistive, resistive, and capacitive sensors. However, these systems can be complex, expensive, data-intensive, and typically used once a medical issue is diagnosed.

In this research, we have designed a digital system to analyze weight distribution on different parts of the foot. The system employs pressure sensors to capture the distributed pressure on the foot, transferring this input to an embedded system for processing. The processed data is then displayed on a screen, providing a visual representation of the weight distribution. We tested the system on 200 participants, comprising an equal number of males and females (100 males and 100 females). The analytical results demonstrate that the foot weight distribution system offers insights into the body's musculoskeletal system and its mechanics. Moreover, the system can identify abnormalities in body mechanics, which can be used as a diagnostic tool for detecting potential issues. By analyzing the data, we aim to contribute to the understanding of human bio-mechanics and providing a means for the early detection of musculoskeletal and mechanical disorders.

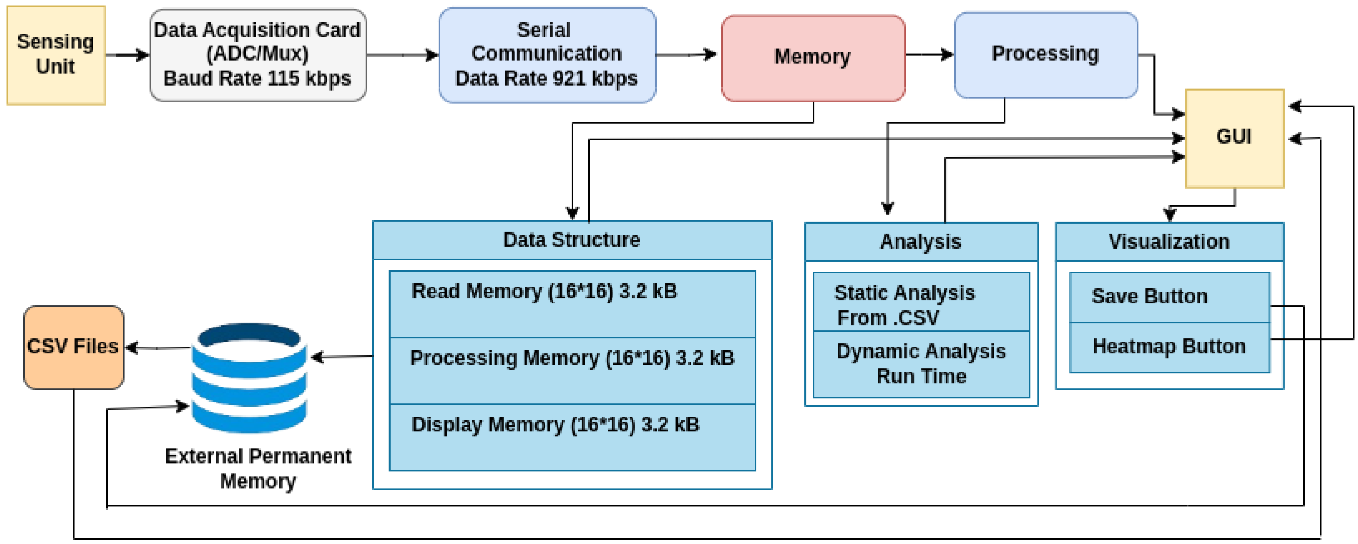

Fig. 1. Detailed Software/Hardware Architecture of Foot Weight Distribution System

II. Related Work

The study of foot weight distribution and gait analysis is an emerging field, and comparatively less research data is available directly related to the topic. Our case study found that weight distribution in a static position is rarely addressed, and research in this field is limited, though there is a need and potential for further investigation.

Abdul Razak et al. [6] reviewed existing systems and proposed a platform-based plantar pressure measurement system using piezoelectric sensors. The proposed work uses a platform fixed on the ground to determine weight distribution. The platform is equipped with sensors, and the case study clarifies the basic concept of weight analysis.

Fragoon Muhammed et al. [7] designed a system to measure body weight distribution and detect diabetes using a vibrotactile sensation technique. The system also uses optical sensors for further weight analysis.

Mitul Vyas et al. [8] proposed a system focusing on weight distribution in young and old people, calculating differences in weight distribution with age.

Oishee Mazmuder et al. [9] developed a wireless data acquisition device that measured foot weight distribution on the plantar surface using capacitive sensors, a microcontroller, and a wireless sensor.

Frederick and Ahnryu et al. [10] developed a foot pressure distribution system that introduces a Long Short-Term Memory (LSTM) deep learning model for predicting pressure distribution using a limited number of pressure sensors embedded in an insole.

Weijun and Rencheng et al. [11] researched gait analysis using various motion sensors, including accelerometers, gyroscopes, and magnetoresistive sensors, proposing a wearable sensor system for detecting and analyzing human body gait dynamics.

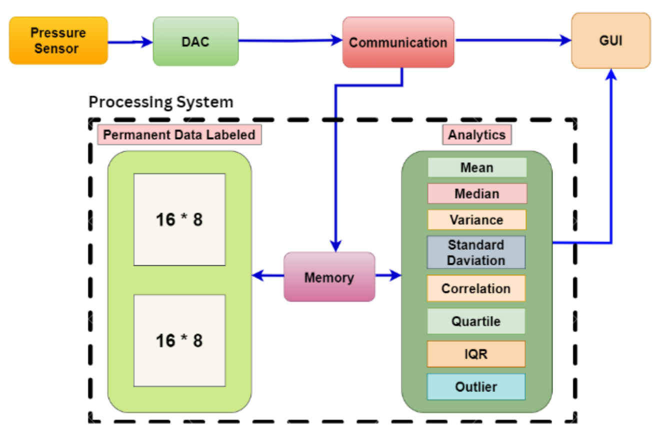

Fig. 2. Block Diagram of Foot Weight Distribution System

Wang and Chengxiang et al. [12] performed precise footprint analysis using statistical methods and piezoresistive films. Their experimental setup includes data acquisition hardware for sensing plantar pressure distribution and software for processing the collected data.

Chun et al. [13] explained pressure distribution on feet while standing on flat and sloped surfaces, showing that the right foot generally applies more pressure. On inclined surfaces, pressure shifts more towards the front of the foot, which may affect foot health and orthotic design.

III. Intelligent Digital System for Foot Weight Distribution

Our proposed system senses pressure on different parts of the foot using an intelligent algorithm to identify and predict musculoskeletal deformities and issues such as foot ulcers, providing a means for early detection of musculoskeletal and mechanical disorders.

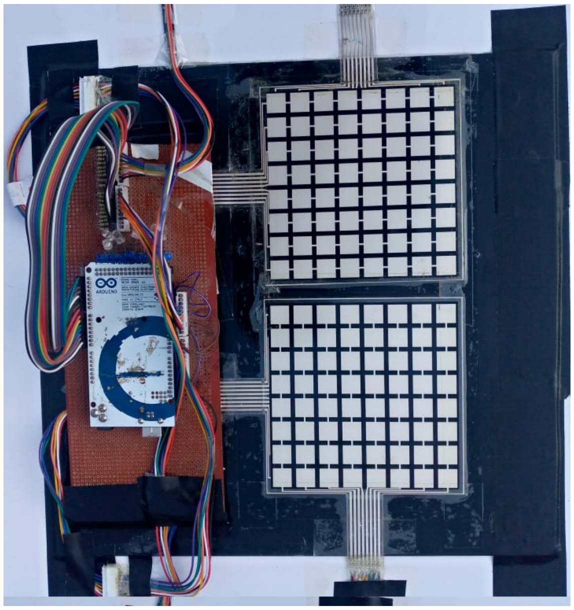

Fig. 3. 16 x 8 Single Foot Weight Distribution System

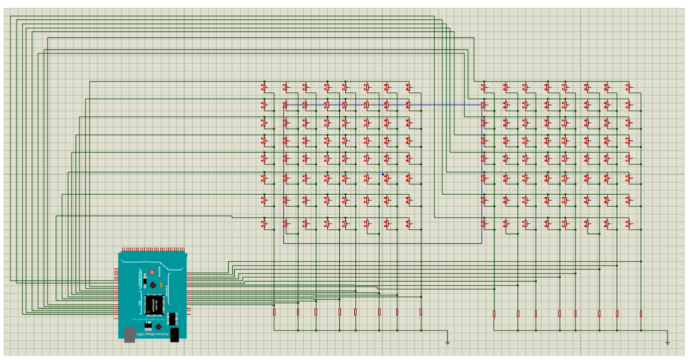

Fig. 4. Schematic Diagram of Hardware Design

This system uses Force Sensing Resistor (FSR) sensors to measure pressure distribution across different parts of the foot. The DAQ (Data Acquisition System) converts the analog signals from the sensors into digital values for further processing [14]. The DAQ also performs amplification and filtration to ensure high-quality data for analysis. Finally, the communication system transfers the data from the DAQ to the processing system. The processing system executes an intelligent algorithm that analyzes the mean, variance, standard deviation, correlation, quartiles, interquartile range (IQR), and outliers within the dataset and displays the results on the screen in graphical form. A quartile is a statistical measure that divides data into four equal parts: Q1 (the first quartile) includes the lowest 25%, Q2 (the median) covers 50%, and Q3 (the third quartile) spans up to 75% of the data. This technique helps analyze variations in foot pressure data. The Interquartile Range (IQR) measures the variation between Q1 and Q3, providing insights into differences between the forefoot and rearfoot. Outlier detection identifies values significantly different from the majority, helping to pinpoint unusual data points and ensure accurate analysis.

The complete architecture of the foot weight distribution system is subdivided into sub-sections: (a) Sensing Platform, (b) Data Acquisition, (c) Processing System, and (d) Test Experiment.

A. Sensing Platform

The sensing platform of a single foot uses 2 FSR (Force Sensing Resistor) sensors in matrix form with 8×8 strain gauges, each with a diameter of 12 mm and a sensitivity range from 200 g to 100 kg. While selecting the sensing platform for weight distribution systems, the following parameters are considered:

- Transfer Function: An ideal or theoretical outputstimulus relationship exists for every sensor, which helps in designing and calibrating real-world sensors.
- Hysteresis: Hysteresis is the response of the sensor at the same point while loading and unloading. It is usually noted at 50% of the input range and caused by mechanical components and electronic circuits.
- Linearity: Linearity is the response of the sensor to applied input when plotted. FSR sensors show non-linearity as the resistance change is not perfectly proportional to the applied force.
- Temperature Sensitivity: Temperature sensitivity indicates that the sensor reading may change with ambient temperature. FSR sensors operate between -30 °C to 60 °C.
- Full-scale Input: The maximum input value that can be applied to the sensor without causing significant inaccuracy or damage.
- Full-scale Output: The algebraic difference between the electrical output signals measured with maximum and minimum input stimuli.
- Sensing Area of the Sensor: The sensing area should be large enough to measure proper foot weight distribution. The sensing area for a complete single-foot design is 97.5mm by 195mm. As foot sizes vary, using smaller strain gauges or sensors in an array can achieve higher resolution and capture pressure differences throughout the foot.

B. Data Acquisition System

The data acquisition system is further subdivided into the Analog to Digital Converter and Communication Module, both integral parts of this system.

1) Analog to Digital Converter: The Analog-to-Digital Converter (ADC) converts analog signals of FSR sensors into digital signals to be processed by the processing system [15], [16]. We have used an Arduino Mega for digitization. Its sampling rate is 10k samples per second, with a resolution of 10 bits, and it performs simple processing, including time delay and serial transmission between the sensing platform and the visualization element.

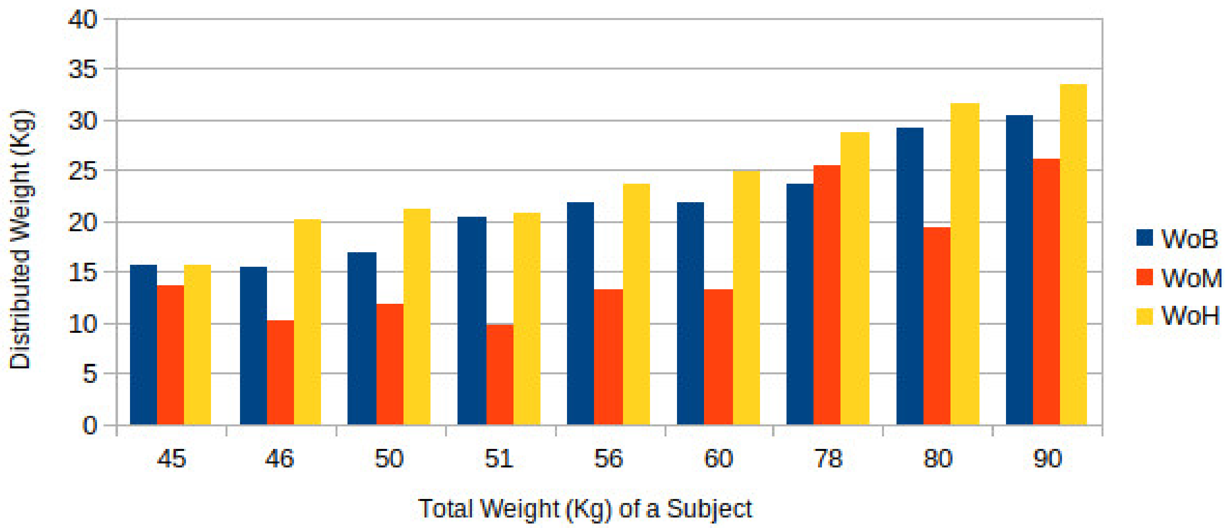

Fig. 5. Female Weight Distribution

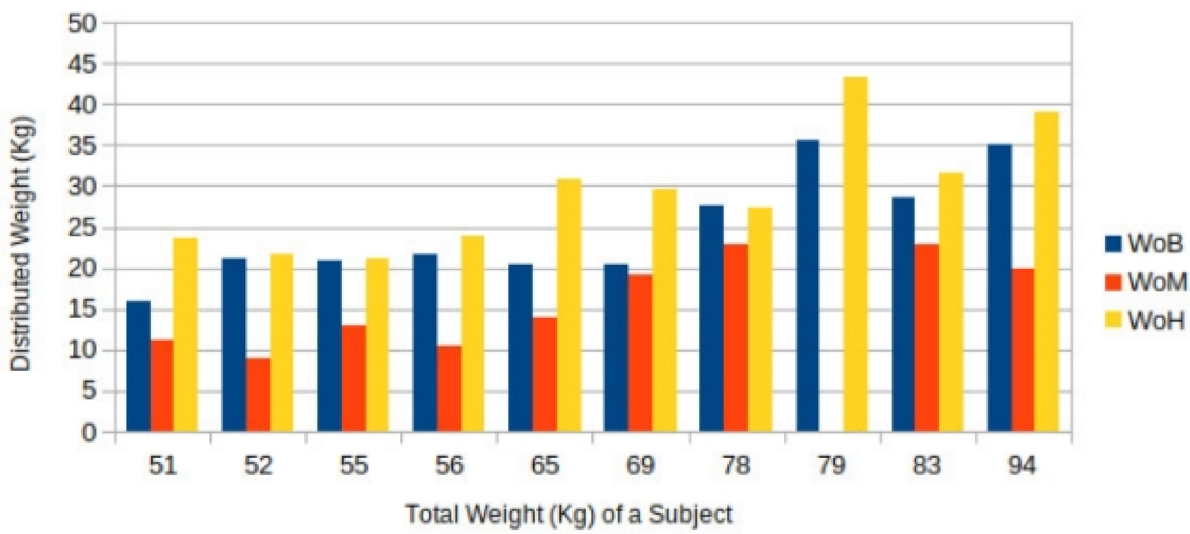

Fig. 6. Male Weight Distribution

2) Communication Module: The Communication Module transmits acquired data from the Data Acquisition System to a USB port using serial communication. This communication is facilitated by the Arduino Mega board using its serial pins. The maximum data transfer rate of the Communication Module is 574kB per second, enabling it to handle parallel data from up to 25 sensors. The Arduino Mega uses its serial ports (RX and TX pins) to communicate with the computer.

C. Processing System

We have employed a Single Board Computer [17] (Intel Dual Core) for visualizing the final results of weight distribution. Libraries of Python 3.10 (such as sklearn, numpy, pandas, tkinter, matplotlib, and streamlit) are used for data processing and visualization [18]. A user-friendly Graphical User Interface (GUI) is created using Streamlit, which can run efficiently on low-resource systems. Additionally, we use machine learning algorithms like Support Vector Machine (SVM) to add intelligence to the system. This helps in identifying abnormalities and classifying foot types (flat, high-arched, neutral) based on the analyzed sample data. The foot weight distribution is categorized as follows: Forefoot: 28-35%, Medial: 14-19%, Heel: 46-54% of the total body weight.

D. Test Experiment

To test the system, we considered 200 participants (100 males, 100 females). Initially, the weight of all participants was measured using a Taurus weighing scale (up to 140kg).

After weighing, participants stood on the weight distribution platform. Care was taken to ensure proper positioning on the platform to facilitate accurate weight distribution measurements.

For linearity readings, weights (1kg each) up to 7kg were added as available, and for hysteresis calculation, these weights were removed one by one. The system was tested at temperatures of 5°C, 10°C, 15°C, 20°C, 25°C, 30°C, 40°C, and 45°C. The system showed no significant changes in values with varying temperatures. Creep may occur in pressure foam thin sheets due to cyclic loading as participants repeatedly stand on the sensing platform.

IV. Results and Discussion

Data was gathered from multiple subjects (as discussed in Section III-D). For each subject, real-time sensor values for each foot were collected and converted to weight distribution using the following formulas:

$$WoB = \frac{Strain\ Gauge_B}{Strain\ Gauge_T} \times W_p \tag{1}$$

$$WoM = \frac{Strain\ Gauge_M}{Strain\ Gauge_T} \times W_p \tag{2}$$

$$WoH = \frac{Strain\ Gauge_H}{Strain\ Gauge_T} \times W_p \tag{3}$$

where W_p is the weight of the person. The weight distribution across three major parts of the foot relative to the total weight is shown in the graphs with different colors.

From the obtained results, it is evident that most body weight is distributed in the ball and heel of the foot, with less weight in the middle of the foot. More weight is concentrated in the heel and slightly less in the ball area of the foot.

Figures 5 and 6 illustrate two abnormal cases: one for a female and one for a male individual. One female participant weighing 78kg had most of her weight distributed in the middle of the foot, which deviated from typical weight distribution patterns. One male participant weighing 79kg had no weight distributed in the middle of the foot, an extremely abnormal case, causing foot pain and other ailments.

V. Conclusion

In this work, we proposed a novel digital system that determines weight distribution across different parts of the foot. The system utilizes a data acquisition system to collect data from the foot using sensors placed in various locations. Statistical analysis techniques are then applied to understand foot patterns and identify defects in the body. We validated the system by analyzing data from 200 participants (100 males and 100 females).

VI. Acknowledgment

The research leading to these results has been funded by Unal Color of Education Research and Development (UCERD) Private Limited Islamabad and FootAnalytic. The authors would like to thank the Barcelona Supercomputing Centre, Pakistan Supercomputing Centre, and Centre for AI and Big Data (CAID) Namal University Mianwali for their support.

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