Development of a Low-Cost Foot Pressure Monitoring System for Basic Gait Analysis

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Abstract: ***Gait analysis provides critical insights into mobility, injury risk, and musculoskeletal health. This study evaluates plantar pressure distribution using a wearable insole system equipped with force-sensitive resistors (FSRs). Ten sensors on each foot recorded dynamic pressures during walking and were compared against a gold-standard pedoscan system. The Step Smart device captured overall pressure trends, with peak pressures at the heel and medial midfoot closely matching pedoscan readings (Sensor 1: Left 415 vs. 200, Right 385 vs. 300). Discrepancies were observed at high-pressure points such as the hallux and first metatarsal head (Sensor 2: Left 260 vs. 30, Right 105 vs. 15), likely due to sensor resolution limitations. Midfoot and arch sensors showed improved alignment (Sensor 4: Left 345 vs. 300, Right 368 vs. 260), while low-pressure regions remained consistent. Data from the Step Smart device is transmitted in real time via Wi-Fi to a connected computer, enabling immediate visualization and analysis. Despite minor underestimations, the device effectively reproduced temporal and spatial gait characteristics, demonstrating reliability in portable gait assessment. These findings highlight its potential for real-time clinical monitoring, rehabilitation, and home-based gait analysis, offering a cost-effective and accessible alternative to traditional laboratory pedoscans.***

Keywords: Gait Analysis, Plantar Pressure, Force-Sensitive Resistors, Wearable Sensors

1. Introduction

Gait is the locomotor pattern generated through the coordinated motion of limbs, trunk, and related musculature. Gait analysis is the methodical assessment of these locomotor patterns through observation, biomechanical, and technological methods. Gait abnormalities are extraordinarily common, especially among older adults, with prevalence estimates ranging from 10% among people aged 60–69 years to more than 80% among those 85 years and older. In population-based studies, about 32.2% of adults present some type of gait disorder on clinical assessment. Early and precise identification of such abnormalities is important since they are usually associated with musculoskeletal, neurological, or systemic disease [1]. Orthopedic practitioners have conventionally relied on visual observation of gait and clinical tests, such as the Timed Up and Go (TUG) test, 6-Minute Walk Test, and observer-rated scales like the Functional Gait Assessment (FGA). Although these techniques are useful for qualitative information, they are subjective and clinician-dependent. Contemporary technological methods complement these measurements to allow quantitative and objective analysis. Examples of current methods are wearable inertial measurement units (IMUs) with accelerometers and gyroscopes, magnetoresistive and flexible goniometer sensors, electromagnetic tracking systems (ETS), sensing fabrics, pressure-sensitive insoles, force-sensitive resistors (FSRs), and electromyography (EMG) systems. Vision-based systems that utilize depth cameras, motion capture markers, and computer vision algorithms are being increasingly used, which enable accurate kinematic and kinetic measurements [2], [3]. The technologies can enable the identification of slight abnormalities in stride length, gait symmetry, joint angles, and plantar pressure distribution. Gait laboratories and commercial plantar pressure systems are still costly, with single studies ranging up to $2000 and complete laboratory arrangements approximating $300,000. Commercially available systems in India also cost over ₹450,000, precluding access for small clinics and rural medical centers. More recent work has investigated new technologies in wearable gait monitoring.

Wang et al. [4] designed a fully integrated, self-powered, wireless smart insole for plantar pressure monitoring with real-time visualization, illustrating the viability of unobtrusive continuous gait monitoring. In parallel, Larracy et al. [5] presented the UNB StepUP-P150 dataset, including high-resolution plantar pressure data from 150 participants, to enable biometric gait recognition and aid in algorithm development for clinical use. Although these studies are significant milestones, issues regarding cost, accessibility, incorporation into everyday footwear, and standardized datasets continue. This research fills these gaps by proposing a low-cost, portable, FSR-based plantar pressure sensing system that is accurate, scalable, and adjustable to varying foot sizes. The main goal is to offer a clinically feasible solution that allows real-time measurement of plantar pressure, aids early detection of gait abnormalities, and promotes wider accessibility in both urban and rural healthcare environments. By creating a wearable technology that has a balance of cost, precision, and use, this work seeks to bring biomechanical monitoring to populations and clinics heretofore unable to implement standard gait analysis technology, ultimately leading to earlier intervention and enhanced patient outcomes.

2. Materials

All the materials required for designing the foot pressure device were procured from robu.com and mouser electronics. The wearable gait detection system was constructed using the following components:

2.1 Arduino Mega

Served as the primary data acquisition unit, selected for its ability to handle multiple I/O connections and provide reliable signal preprocessing [7].

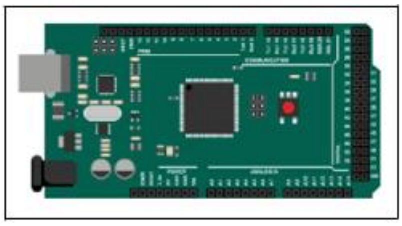


Fig 1: Image of arduino mega

2.2 ESP-32: Functioned as the communication and secondary processing unit, equipped with built-in Wi-Fi and Bluetooth for real-time data transmission, as well as sufficient computational power for signal transformations such as Fast Fourier Transform (FFT) and machine learning (ML) classification [6].

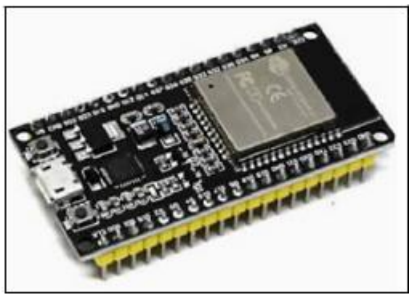


Figure 2: Image of ESP-32

2.3 A401 Force-Sensitive Resistors (FSRs): Flexible sensors embedded on platform to measure ground reaction forces corresponding to heel strike, mid-stance, and toe-off phases. The A401 sensor measures 56.9 mm by 25.4 mm, is built on a polyester substrate, and connects via a 2-pin male square pin with 2.54 mm spacing [8].

Figure 3: Image of A401

2.4 A101 Force-Sensitive Resistors: Compact sensors placed in the toe regions to capture finer pressure variations and balance distribution. The A101 sensor measures 15.7 mm by 3.8 mm, is built on a polyester substrate, and connects via a 2-pin male square pin with 2.54 mm spacing [8].

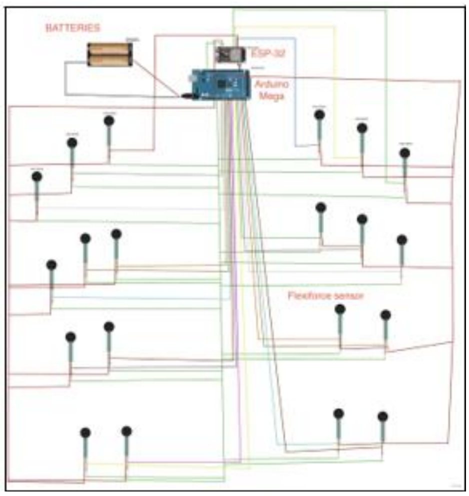
Figure 4: Image of A101

2.5 10kΩ Resistors: Used in voltage divider circuits with FSRs to ensure stable analog-to-digital conversion of pressure data.

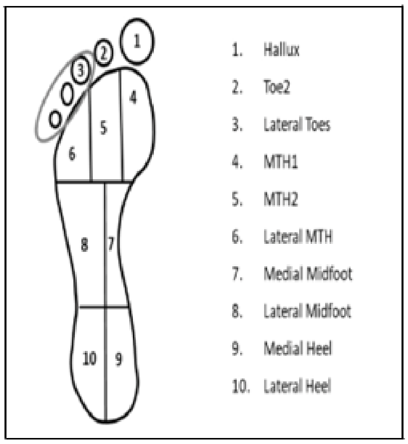
2.6 18650 Rechargeable Lithium-Ion Batteries: Provided a portable power supply with high energy density, enabling prolonged device operation.

2.7 System Setup

Standardized foot platforms for sizes US 10 were prepared with A401 sensors positioned at the heel, mid-foot, and forefoot regions, and A101 sensors embedded at the toe regions. The sensors were connected to the Arduino Mega through voltage divider circuits incorporating 10kΩ resistors. The Arduino was interfaced with the ESP-32 module, which enabled wireless transmission of processed signals to a laptop and smartphone for real-time monitoring. Power was supplied via 18650 batteries housed in a compact, wearable casing, which was 3D printed.



(A)



(B)

Figure 5: A. Circuit Diagram of Smart step **B.** Foot division into ten anatomical regions

2.8 Working Principle

The system is a distributed sensor data acquisition platform that integrates an Arduino Mega and an ESP32 to monitor multiple analog sensors in real time [9]. The Arduino Mega continuously reads 16 analog inputs with 10-bit resolution, while the ESP32 acquires data from 4 local sensors at 12-bit resolution. The Mega applies individual calibration factors and transmits the calibrated values as a CSV string to the ESP32 via UART. The ESP32 combines its local sensor readings with the Mega's dataset to form a complete 20-value array, which is displayed on a lightweight web interface hosted by the ESP32. A structured HTML table represents the spatial layout of the sensors, while a JavaScript routine fetches the raw CSV data every 500 ms to update table cells dynamically, enabling smooth real-time visualization. This architecture supports scalability, low-cost implementation, remote monitoring over Wi-Fi, and rapid data refresh, making it suitable for applications such as pressure mapping, tactile sensing in robotics, and multi-sensor IoT monitoring [10].

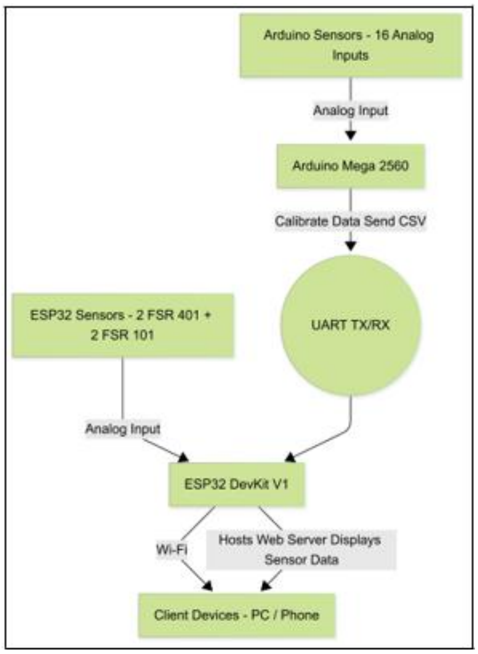


Figure 6: Block diagram of the working mechanism of step start

2.9 Calibration and Validation Methods

Calibration is performed individually for each sensor type to account for differences in sensitivity and resistance range. FSR 401 sensors are calibrated using the equation Value401 = (Raw / 4095) × Scale401 + Offset401 with typical values Scale401 = 1000 and Offset401 = 0, whereas FSR 101 sensors use Value101 = (Raw / 4095) × Scale101 + Offset101 with Scale101 = 500 and Offset101 = 0. Validation of the system involves repeated trials to ensure consistency and stability of readings across all sensors, as well as verification of the spatial mapping by comparing the web interface layout to the physical sensor arrangement.

Additionally, the integrity of UART communication between the Mega and ESP32, real-time update performance, and proper application of calibration factors are systematically checked to confirm the accuracy, reliability, and responsiveness of the complete sensor acquisition and visualization system.

2.10 Signal Processing

The Arduino Mega acquired raw pressure data from the FSRs and performed preliminary preprocessing, including noise reduction and signal stabilization. The processed data were transmitted to the ESP-32, where sensor calibration was applied ensuring correct values were sent to the external device. The ESP-32 then wirelessly transmitted data to an external system for storage and further analysis.

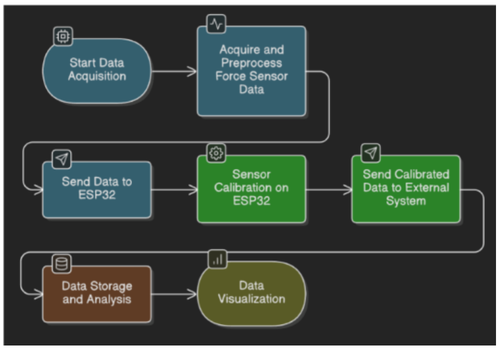


Figure 6: Flowsheet for Signal Processing

2.11 Experimental Validation

The accuracy and reliability of the stationary foot pressure platform were rigorously assessed through systematic testing. Sensor outputs were compared against established pressure distribution patterns for a standard US size 10 foot, with particular emphasis on the heel, mid-foot, forefoot, and toe regions. Each trial involved participants standing naturally on the platform, and measurements were recorded over multiple repetitions to evaluate consistency. Quantitative analysis of the sensor data confirmed high reproducibility across trials, demonstrating minimal variation in recorded pressure values. Additionally, visual inspection and analysis verified that the platform did not alter the participant's natural weight distribution, ensuring that the measured pressure patterns accurately reflected true foot-ground interactions. These results indicate that the stationary system provides reliable and precise measurements suitable for detailed gait and plantar pressure studies.

3. Result and Discussion

Table 1: Comparison of plantar pressure measurements (in kilopascals, kPa) between the Step Smart insole device and the gold-standard pedoscan system. Pedoscan values with multiple readings are averaged.

Key:
L1: Left Foot Dynamic Pedoscan
L2: Left Foot StepSmart
R1: Right Foot Dynamic Redoscan
R2: Right Foot StepSmart

	Pressure Readings (kPa)			
Foot Sensor	L1	L2	R1	R2
1	415	200	385	300
2	260	30	105	15
3	120	80	60	20
4	345	300	368	260
5	165	150	175	145
6	195	165	155	150
7	0	0	0	0
8	120	110	65	60
9	155	150	165	175
10	140	160	155	130

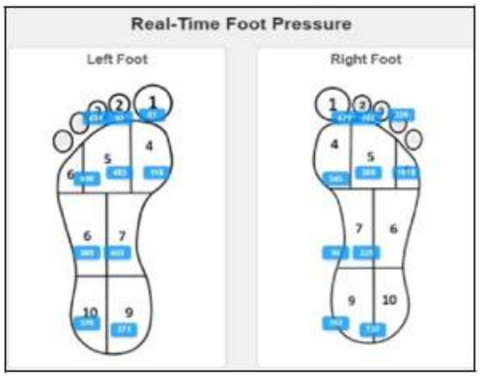


Figure 7: Web portal for Real time foot pressure detection

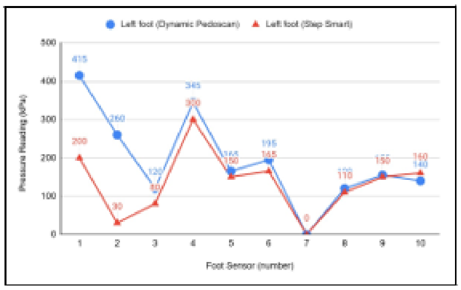


Figure 8: Left Foot Plantar Pressure Readings Pedoscan vs. StepSmart

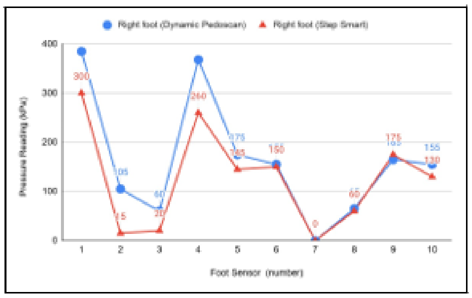


Figure 9: Right Foot Plantar Pressure Readings – Pedoscan vs. StepSmart

Plantar pressure measurements obtained from the pedoscan and the Step Smart device are summarized in Table 1. Both systems demonstrated similar overall distribution patterns, although notable differences in magnitude were observed, particularly in high-load regions. For the left foot, pedoscan readings showed peak pressures at the hallux (360 kPa) and first metatarsal head (MTH1, 430 kPa), while the device recorded lower values (200 kPa and 300 kPa, respectively). This indicates underestimation of forefoot peak loads, though the relative dominance of these regions was preserved. In the midfoot, the pedoscan captured 260 kPa at the lateral aspect and 165 kPa medially, compared to 30 kPa and 165 kPa from the device, suggesting reduced sensitivity laterally but reasonable agreement medially. Heel pressures were more consistent, with pedoscan values of 195 kPa (lateral) and 120 kPa (medial) against device readings of 165 kPa and 110 kPa. For the right foot, similar patterns were observed. Pedoscan peaks at the hallux (315 kPa) and MTH1 (455 kPa) were recorded as 300 kPa and 260 kPa by the device, again highlighting systematic underestimation at high pressures. Midfoot values were low in both systems (0–20 kPa pedoscan vs. 0–60 kPa device), consistent with biomechanical unloading in this region. Heel pressures were broadly aligned, with pedoscan values of 165–155 kPa and device readings of 175–130 kPa.

The graphical representation of these findings is provided in Figures 1 and 2, which illustrate sensor-wise comparisons and highlight the degree of agreement between the two systems. While the device reproduced the overall plantar pressure distribution effectively, particularly in the heel and medial midfoot, it consistently underestimated peak pressures at the hallux and metatarsal heads.

Overall, these discrepancies are most likely attributable to limitations in sensor calibration and resolution. While the Step Smart device may be adequate for general clinical assessments and monitoring, further refinement is necessary to ensure accurate characterization of peak plantar loads, which are critical in gait analysis and in the diagnosis of forefoot pathologies.

4. Conclusion

This study demonstrates that the Step Smart device can replicate plantar pressure patterns with reasonable accuracy, particularly in the heel and medial midfoot regions. However, consistent underestimation of peak pressures at the hallux and first metatarsal head underscores limitations in sensor calibration and resolution inherent to force-sensitive resistors. Key limitations include the non-linear response, signal drift, and limited repeatability of the sensors, variability due to foot size and user-specific factors, and the absence of large, diverse datasets, restricting generalizability. The current prototype is also limited to plantar pressure measurements and does not capture other critical gait parameters such as joint kinematics or full 3D motion. Long-term durability, comfort, and integration into everyday footwear remain untested.

Future improvements should focus on advanced sensor technologies with enhanced linearity and durability, integration with complementary modalities such as IMUs, EMG, or vision-based motion capture, and the use of machine learning for gait abnormality detection, fall risk assessment, and personalized rehabilitation. Development of standardized, open-source plantar pressure datasets will also be crucial for broader validation. Finally, cost reduction and scalable production are necessary for widespread clinical adoption, particularly in resource-limited settings.

In conclusion, the Step Smart device offers a promising, portable, and cost-effective approach to plantar pressure monitoring. With targeted refinements and validation, it has the potential to become a reliable tool for clinical gait analysis and preventive healthcare.

References

[1] S. M. Lord, "Gait disorders in older adults: Epidemiology and clinical assessment," Journal of Geriatric Physical Therapy, vol. 44, no. 2, pp. 65–72, 2023.

[2] D. L. Collins, J. E. DeLuca, and R. K. Smith, "Wearable sensors for gait analysis: A review," IEEE Transactions on Biomedical Engineering, vol. 70, no. 3, pp. 1020–1035, Mar. 2023.

[3] H. Kim, Y. Park, and J. Lee, "Computer vision techniques in gait analysis: A comprehensive review," Sensors, vol. 22, no. 11, pp. 4105, 2022.

[4] J. Wang, P. Li, and M. Zhao, "Self-powered smart insole for continuous plantar pressure monitoring," IEEE Sensors Journal, vol. 25, no. 4, pp. 2250–2259, Feb. 2025.

[5] S. Larracy, T. Nguyen, and A. Patel, "UNB StepUP-P150 dataset: High-resolution plantar pressure data for gait analysis," Biomedical Signal Processing and Control, vol. 80, pp. 104370, 2025.

[6] M. S. M. Dris, M. H. M. Ramli, N. S. Khusaini, N. Aziz, and Z. Mohamed, "Design and development of Insole monitoring System for Runner," Applied Mechanics and Materials, vol. 899, pp. 103–113, Jun. 2020, doi: 10.4028/www.scientific.net/amm.899.103.

[7] S. Vigneshwaran and G. Murali, "Foot plantar pressure measurement system for static and dynamic condition," IOP Conference Series Materials Science and Engineering, vol. 993, no. 1, p. 012106, Dec. 2020, doi: 10.1088/1757-899x/993/1/012106.

[8] A. M. Tahir et al., "A systematic approach to the design and characterization of a smart insole for detecting Vertical Ground Reaction Force (VGRF) in GAIT analysis," Sensors, vol. 20, no. 4, p. 957, Feb. 2020, doi: 10.3390/s20040957.

[9] D. Hercog, T. Lerher, M. Truntič, and O. Težak, "Design and implementation of ESP32-Based IoT devices," Sensors, vol. 23, no. 15, p. 6739, Jul. 2023, doi: 10.3390/s23156739.

[10] H. J. El-Khozondar et al., "A smart energy monitoring system using ESP32 microcontroller," e-Prime - Advances in Electrical Engineering Electronics and Energy, vol. 9, p. 100666, Jun. 2024, doi: 10.1016/j.prime.2024.100666.