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Original research article

Design and Evaluation of a Smart Insole System for Real-Time Gait and Plantar Pressure Monitoring

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ABSTRACT

Wearable sensor systems offer new opportunities for continuous, non-invasive monitoring of gait and plantar pressure, providing insights for rehabilitation and mobility assessment. This study presents a lightweight, minimally intrusive smart insole system integrating five force-sensitive resistors, microcontroller-based readout electronics with Bluetooth low energy communication, and a smartphone application for data visualization, storage, and analysis. The microcontroller (nRF52840) samples force sensitive resistor (FSR) signals at 100 Hz, transmits data wirelessly, and is powered by a rechargeable lithium-ion battery housed in a compact 3D-printed enclosure designed for minimal impact on user comfort and mobility. To assess the influence of insole material on sensor performance, testing was conducted using direct sensor insoles and 3D-printed thermoplastic polyurethane (TPU) insoles of two hardness levels (95A and 65A Shore). Results from a subject walking along a defined path demonstrate consistent trends between left and right insoles, while the measured analog-to-digital converter (ADC) signals indicate that softer insole materials reduce peak sensor readings. The proposed system provides a versatile platform for real-time gait monitoring and personalized gait rehabilitation, highlighting the critical interplay between insole material properties and sensor performance.

Key words: *3D-printed smart insoles, wearable sensors, force-sensitive resistors, gait analysis.*

1. INTRODUCTION

Advances in wearable technology have enabled the development of smart systems capable of monitoring human motion and physiological parameters in real time. Among these, sensor-embedded smart insoles offer a non-invasive approach for assessing gait, balance, and plantar pressure distribution, which is particularly valuable for clinical applications such as post-stroke rehabilitation or other mobility impairments. Integration of force-sensitive resistors (FSRs) with microcontroller-based readout electronics and wireless communication allows accurate, continuous monitoring while maintaining comfort and minimal interference with natural movement.

Over the past decade, the study of human motion and plantar pressure has gained increasing attention in wearable technology research. Early gait analysis relied primarily on laboratory-based systems, including force plates and motion capture setups, which provide high accuracy but are limited in portability and real-world applicability [1–3]. These limitations have spurred the development of wearable solutions capable of continuous monitoring in everyday life.

Smart insoles equipped with FSRs and other pressure sensors have emerged as practical tools for gait assessment and rehabilitation monitoring. FSRs are lightweight, low-cost, and easily integrated with microcontrollers, making them well-suited for wearable systems [4, 5]. Several

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studies have demonstrated the utility of FSR-based insoles for capturing plantar pressure distribution, temporal gait parameters, and balance metrics in both healthy individuals and patients with mobility impairments [6–8]. Strategic placement of sensors is critical for accurately detecting key biomechanical events such as heel strike, midfoot loading, and forefoot push-off [9, 10].

Continuous plantar pressure data have enabled the development of personalized gait rehabilitation protocols. Real-time feedback from wearable insoles has been shown to improve gait symmetry, balance, and mobility in post-stroke patients and individuals with orthopedic conditions [11, 12]. Companion smartphone applications facilitate intuitive visualization, storage, and analysis of gait parameters, enhancing usability for both clinicians and patients [13].

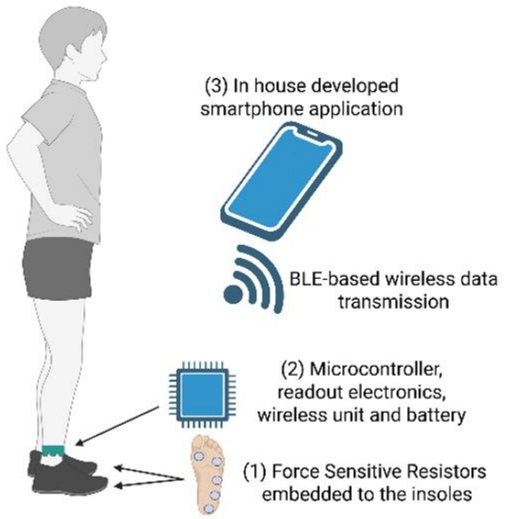
Insole material properties also significantly affect sensor readings. Recent studies have explored 3D-printed insoles with varying hardness to optimize both comfort and measurement accuracy [14, 15]. Careful calibration of the interaction between the foot, insole material, and embedded sensors is essential to ensure reliable data acquisition without compromising natural gait patterns.

Previous studies have highlighted the importance of real-time feedback and data acquisition for improving therapeutic outcomes and designing personalized gait rehabilitation protocols. However, challenges remain in developing systems that are compact, lightweight, and capable of delivering high-fidelity data under practical conditions. In particular, the integration of hardware components with flexible insoles and mobile applications must balance among measurement accuracy, power efficiency, and user comfort.

This study addresses these challenges by developing a lightweight, minimally intrusive smart insole system and evaluating the impact of 3D-printed insole materials on sensor performance. Designed to be adaptable to various types of footwear, it provides reliable data for both clinical and research applications. The primary objective is to evaluate system performance under real-world conditions and demonstrate its potential as a tool for gait analysis and rehabilitation monitoring. By integrating compact electronics, FSRs, and mobile software, the proposed system represents a step toward accessible and effective wearable health-monitoring solutions.

2. SMART INSOLE ELECTRONICS DESIGN

The smart insole system (Fig.1a) integrates three major components: (i) sensor-equipped insoles with five strategically positioned FSRs to capture key plantar pressures, (ii) microcontroller-based readout electronics with Bluetooth Low Energy (BLE) communication, and (iii) a smartphone application for data visualization, storage, and analysis. Fig. 1b presents the hardware prototype of the developed system with the designated FSR positions. The illustration clearly shows all major components, including the sensor layout, embedded electronics, and overall structural arrangement, providing a comprehensive view of the system's physical configuration.



a)

b)

Fig. 1. S*mart insole system: (a) overview of the integrated components, (b) developed hardware prototype*

The electrical schematic of the microcontroller (MCU)-based readout electronics with BLE unit is shown in Fig. 2. The microcontroller is nRF52840 which is powered by rechargeable lithium-ion battery. The charger circuit is based on the BQ25101, with possible two current ratings (50 mA and 100 mA), depending on the nominal capacitance of the battery (the charging current should be approximately 1/10 of its Ah rating). The charging of the battery is done by simply plugging the USB cable (type C connector) to the microcontroller board. The charger will terminate the charging when the battery is at full capacity, preventing damage and overheating if the charger is connected for a prolonged period. Each FSR of the insole is connected to reference resistor of 10 kΩ, forming a voltage divider in which the potential of the junction is defined with Eq. (1):

$$V = \frac{10k\Omega}{10k\Omega + R_{FSR}} \times 3.3V \qquad (1)$$

where R_{FSR} is the resistance of the FSR and it changes accordingly to the applied force on the surface of the FSR, while 3.3 V is the value of the power supply voltage. Readout electronics have connectivity to 5 FSRs. The voltage V given in Eq. (1) is then sampled by the microcontroller's ADC. The ADC conversion is single ended, with a sampling frequency of 100 Hz. The digital form of the measured voltage is then ready to be sent wirelessly to the smartphone using BLE link. The microcontroller program code is developed in C++ within the Arduino Integrated Development Environment (IDE)

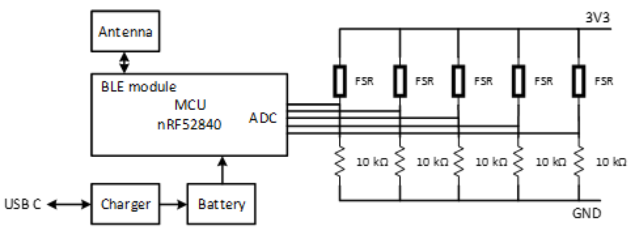


Fig. 2. *Schematic diagram of the battery-powered MCU readout electronics with a BLE module*

The hardware support for BLE protocol is implemented in the microcontroller nRF52840 (Nordic Semiconductor, Trondheim, Norway), requiring only the software development for the interface with the smartphone. Each insole acts as the peripheral of the BLE communication, while the smartphone application is a central device. Such system architecture enables two or more insoles to be monitored with a single smartphone application. This feature can be very useful and convenient when, for example, two feet of the same person.

Smartphone application was developed using MIT App Inventor. The smartphone application has three major blocks. The first one is responsible for BLE-based communication and update of the measured values. The second one is responsible for numerical and graphical presentation of measured values, while the third one is responsible for data storage (local memory of the smartphone). Data storage is performed for each peripheral device separately. The screenshot of the in-house developed application is shown in Fig. 3, while the example of the generated file with measured values for one readout electronics is shown in Fig. 4.

The components used in the embedded electronics are shown in Fig. 5, which also depicts the developed Printed Circuit Board (PCB) designed with minimal dimensions to accommodate all components. To further reduce the electronics' size, a series-connected resistor array was incorporated. This approach not only saves PCB surface area but also requires only a single ground trace.

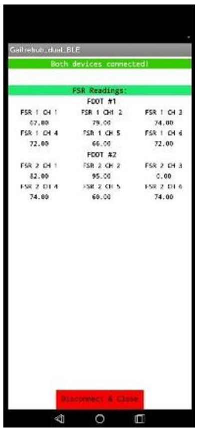


Fig. 3 *Screen shot of developed smartphone application*

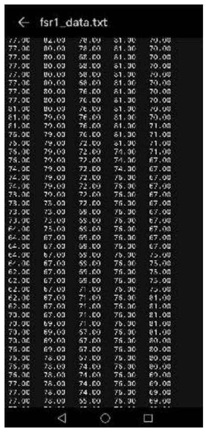


Fig. 4 *Measured values report for one readout electronics module*

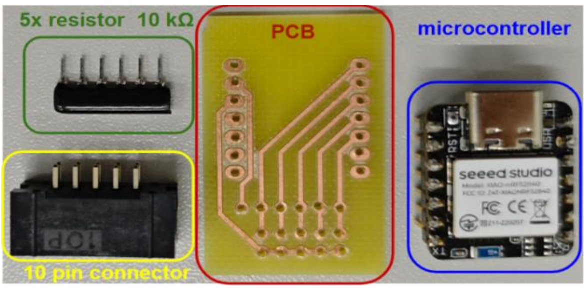


Fig. 5 *Components used in the embedded electronics system*

Since the developed electronics are intended for use by individuals recovering from stroke, careful attention is given to the system's overall dimensions and weight. Excessive size or weight could impede walking and daily activities. The final design measures 35 mm in length and 20 mm in width and is lightweight, ensuring minimal burden on the patient. Fig. 6 shows the electronics assembled on the PCB.

Fig. 6 *Physical size of the electronics module*

In order to connect the sensor insole with the electronics, a 10-pin connector was added, providing a secure connection between the sensor insole and the electronics via a flat cable. At the same time, transferring the electronics to another pair of sensor insoles is very straightforward.

The complete embedded electronics were placed in 3D-printed plastic enclosures to allow for the insertion of a battery and for the entire system to be mounted onto footwear. The enclosures also serve to protect the system from dirt, moisture, and physical damage. Openings were provided on the enclosures for the 10-pin connector and the micro USB port for battery charging. The electronics enclosed in the housing are shown in Fig. 7.

Fig. 7 *Smart insole electronics housed in a plastic enclosure*

3. SYSTEM TESTING

To enable testing under real-world conditions, five FSR sensors were embedded in the insole at key foot locations, spanning from the heel, across the metatarsal region, to the toes. The sensor layout is shown in Fig. 8, while the produced insoles with sensors are presented in Fig. 1b. The sensors, labeled FSR1 to FSR5, are referenced in subsequent readings and diagrams for accurate interpretation of the data.

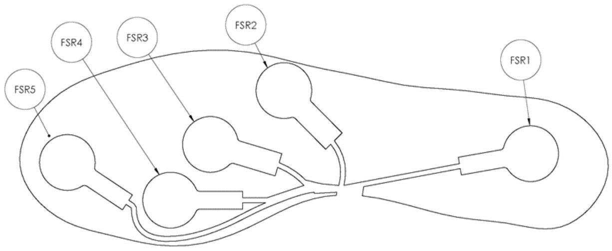


Fig. 8. *FSR sensor layout of the insole*

The electronics and insole system attached to the subject's footwear are shown in Fig. 9. Fig. 9a illustrates how the electronics are secured to the shoe using the laces, positioned so as not to interfere with walking or other activities. The flat cable, visible in the figure, is thin enough not to hinder movement. Fig. 9b shows the system attached to the subject's leg.

Testing of the sensor insoles and embedded electronics was conducted on an adult male subject (*the study has received an ethical exemption from the ethics committee for technical testing*). The system was evaluated in three scenarios. First, the sensor insole was placed directly inside the footwear, and the subject stepped on it. Second, the sensor insole was tested with 3D-printed TPU (Thermoplastic Polyurethane) insoles of two different hardness levels placed on top. The first 3D-printed insole had a hardness of 95A, while the second had a hardness of 65A on the Shore scale. Fig. 10 shows the 3D-printed TPU insoles with the two hardness levels. To illustrate differences in hardness, Fig. 11 shows rubber hardness values according to the Shore scale. Lower values indicate softer rubbers, while higher values correspond to harder rubbers. For 3D printing, TPU materials with hardness between 85A and 95A are most commonly used, representing hard rubber. These materials are widely favored because they are easy to process

(a) (b)

Fig. 9 *Smart insole electronics and sensors: (a) in footwear, (b) on the subject*

Fig. 10 *3D-printed insoles made of TPU with hardness levels of 95A and 65A*

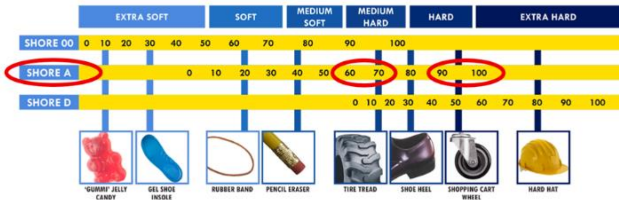
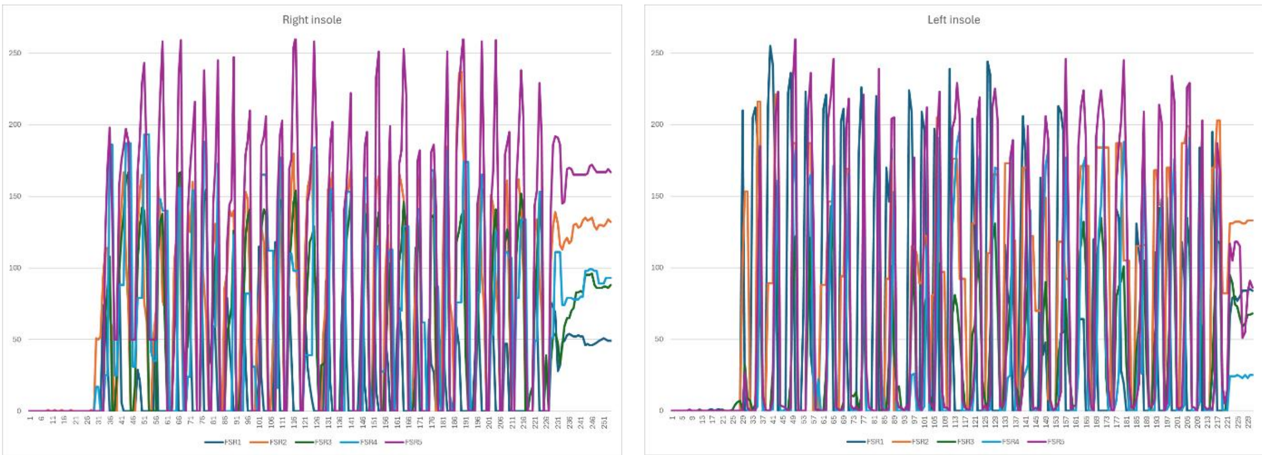


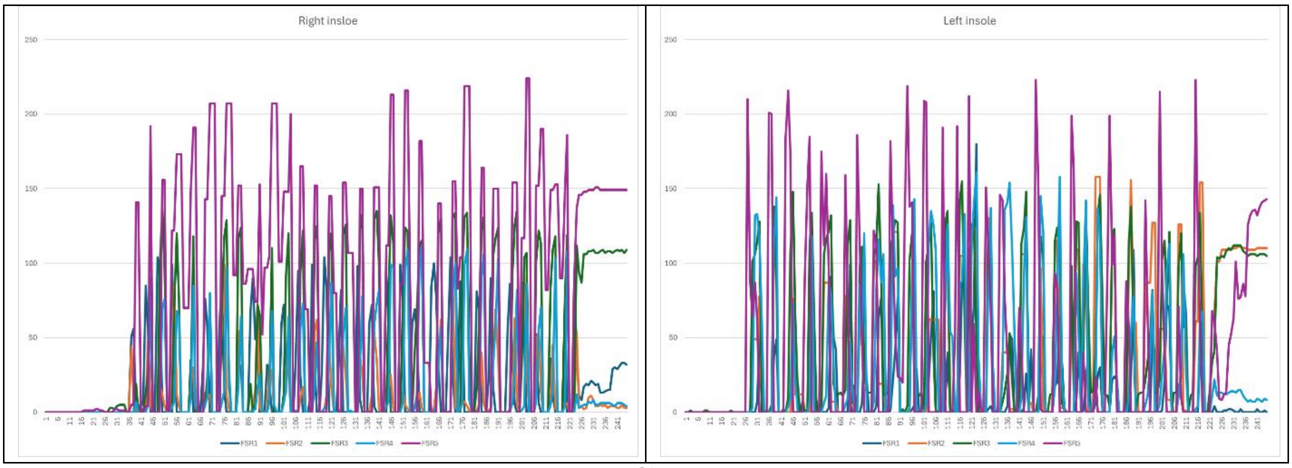
Fig. 11 *Shore hardness of different rubber types [16]*

During testing, both electronic units, for the left and right insoles, were connected via BLE to an Android mobile phone through the GaitReHub application, developed specifically for the project. In the system testing phase, values from the ADC were recorded to evaluate the stability of the entire system during use.

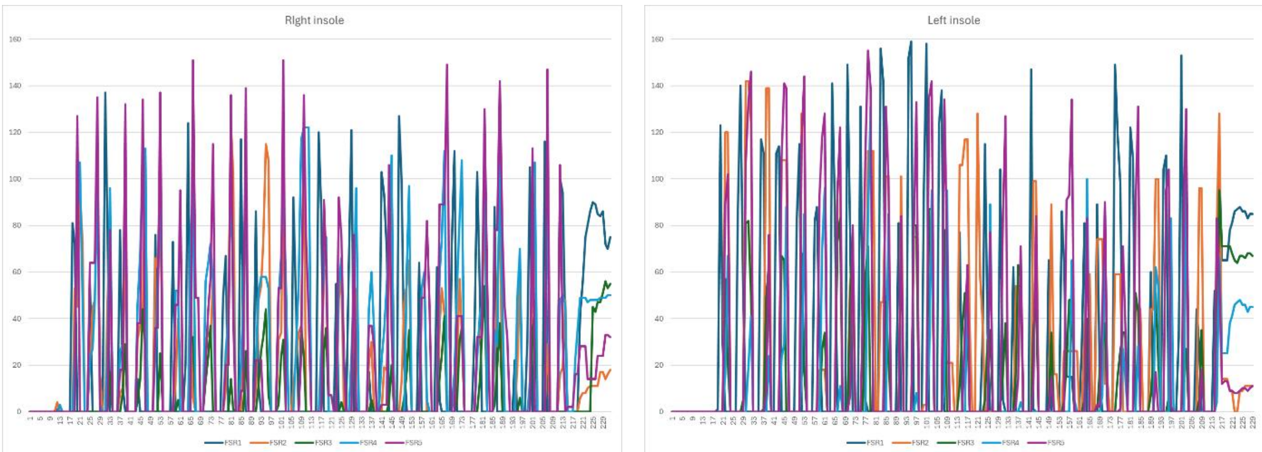
Testing was conducted with the subject taking a total of 60 steps (30 with the left foot and 30 with the right) along a rounded rectangular path measuring 7 m in length and 1.5 m in width. Before the test, the subject sat on a chair for 5–10 seconds with feet lifted to reset the sensors, as the footwear itself exerts some pressure. At the end of the test, the subject stood with both feet on the ground for 5 seconds before saving the data. Measurements were recorded every second and automatically saved for each insole as a *.txt file on the mobile phone. After the test, the *.txt file was transferred to a computer, and diagrams were generated in Excel. Fig. 12 shows the diagrams for the three tests: sensor insole only, 3D-printed TPU insole 95A, and 3D-printed TPU insole 65A. Within each test, the trends and values recorded from the left and right insoles are very similar, with minor differences due to the shape of the path and the natural asymmetry of the human body. On the other hand, when comparing the recorded values from the subject stepping directly on the insole with those obtained while using 3D-printed insoles of different hardness levels, significant differences can be observed.



(a)



(b)



(c)

Fig. 12 *ADC signal in the three tests: (a) without 3D-printed insoles, (b) with a 3D-printed TPU insole of 95A hardness, (c) with a 3D-printed TPU insole of 65A hardness*

The highest values are recorded in the test without 3D-printed insoles (Fig. 12a), followed by the harder insoles (Fig. 12b), and the lowest values occur with the softest insoles (Fig. 12c). This clearly demonstrates that insole material properties, particularly hardness, have a pronounced effect on sensor response, reducing peak ADC values as softness increases. Therefore, the material properties of insoles must be carefully considered and standardized to ensure reliable and accurate data from smart insole sensors.

4. CONCLUSIONS

This study presents the design, development, and preliminary testing of a smart insole system capable of real-time monitoring of plantar pressure and gait parameters. The system integrates five strategically placed FSR sensors, compact microcontroller-based readout electronics with BLE communication, and a smartphone application for data visualization, storage, and analysis. The lightweight and minimally intrusive design ensures that the system does not interfere with natural movement, making it suitable for daily use and clinical applications.

Testing with both direct sensor insoles and 3D-printed TPU insoles of varying hardness demonstrated that insole material properties significantly influence sensor readings, with softer insoles reducing peak ADC values. These findings highlight the importance of careful selection and calibration of insole materials to ensure accurate and reliable data acquisition.

It is important to note that the current study is based on a prototype tested on only a single subject, and no trials with stroke patients or other clinical populations have yet been performed. Consequently, the results should be interpreted as preliminary, and further validation is required before broader clinical application.

Overall, the proposed smart insole system represents a practical and versatile tool for gait analysis, rehabilitation monitoring, and the development of personalized therapeutic protocols. Future work will focus on converting ADC signals into quantitative pressure data, validating the system with larger subject groups, and exploring its potential for continuous, real-world monitoring in diverse clinical and research settings.

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REFERENCES

[1] Perry, J., Burnfield, J. (2010). *Gait Analysis: Normal and Pathological Function* (2nd ed.). CRC Press. https://doi.org/10.1201/9781003525592

[2] Mickle, K.J., Munro, B.J., Lord, S.R., Menz, H.B., Steele, J.R. (2011). Gait, balance and plantar pressures in older people with toe deformities. Gait, balance and plantar pressures in older people with toe deformities. *Gait and Posture*, 34(3), 347-351. https://ro.uow.edu.au/hbspapers/1056

[3] Dias, W.D., Kirkwood, R., Brito, I.C. et al. (2025). Validity and reliability of GAIT Well portable modular system for gait analysis. *Sci Rep*., 15, 36130. https://doi.org/10.1038/s41598-025-92123-4

[4] Xu, W., Huang, M.-C., Amini, N., Liu, J.J., He, L., & Sarrafzadeh, M. (2012). Smart insole: A wearable system for gait analysis. In *Proceedings of the 5th International Conference on PErvasive Technologies Related to Assistive Environments* (PETRA'12). https://doi.org/10.1145/2413097.2413120

[5] Samarentsis, A. G., Makris, G., Spinthaki, S., Christodoulakis, G., Tsiknakis, M., & Pantazis, A. K. (2022). A 3D-Printed Capacitive Smart Insole for Plantar Pressure Monitoring. *Sensors*, 22(24), 9725. https://doi.org/10.3390/s22249725

[6] Tao, J., Dong, M., Li, L., Wang, C., Li, J., Liu, Y., Bao, R., Pan, C. (2020). Real-time pressure mapping smart insole system based on a controllable vertical pore dielectric layer. *Microsyst Nanoeng*., 6, 62. https://doi.org/10.1038/s41378-020-0171-1

[7] Almuteb, I., Hua, R., Wang, Y. (2022). Smart insoles review (2008-2021): Applications, potentials, and future. *Smart Health*, 25, 100301. https://doi.org/10.1016/j.smhl.2022.100301.

[8] Khandakar, A., Mahmud, S., Chowdhury, M. E. H., Reaz, M. B. I., Kiranyaz, S., Mahbub, Z. B., Ali, S. H. M., Bakar, A. A. A., Ayari, M. A., Alhatou, M., Abdul-Moniem, M., & Faisal, M. A. A. (2022). Design and Implementation of a Smart Insole System to Measure Plantar Pressure and Temperature. *Sensors*, 22(19), 7599. https://doi.org/10.3390/s22197599

[9] Santos, V. M., Gomes, B. B., Neto, M. A., Amaro, A. M. (2024). A Systematic Review of Insole Sensor Technology: Recent Studies and Future Directions. *Applied Sciences*, 14(14), 6085. https://doi.org/10.3390/app14146085.

[10] Chen, D., Ghoreishi, N., Olugbon, F., Ansah, S., Huang, M.C., Yu, Q. (2022). Optimal pressure sensor locations in smart insoles for heel-strike and toe-off detection. *2022 IEEE Biomedical Circuits and Systems Conference* (BioCAS), Taipei, Taiwan, 2022, 458-461. doi: 10.1109/BioCAS54905.2022.9948663.

[11] Khoo, I.H, Marayong, P., Krishnan, V., Balagtas, M., Rojas, O., Leyba, K. (2017). Real-time biofeedback device for gait rehabilitation of post-stroke patients. *Biomed Eng Lett*., 7(4), 287-298. doi: 10.1007/s13534-017-0036-1.

[12] Seo, M., Shin, M.J., Park, T.S., Park, J.H. (2020). Clinometric Gait Analysis Using Smart Insoles in Patients With Hemiplegia After Stroke: Pilot Study. *JMIR Mhealth Uhealth.*, 8(9), e22208. doi: 10.2196/22208. PMID: 32909949.

[13] Lunardini, F., Malavolti, M., Pedrocchi, A.L.G., Borghese, N.A., Ferrante, S. (2021). A mobile app to transparently distinguish single- from dual-task

walking for the ecological monitoring of age-related changes in daily-life gait. *Gait & Posture*, 86, 27-32, https://doi.org/10.1016/j.gaitpost.2021.02.028.

[14] Chatpun, S., Dissaneewate, T., Kwanyuang, A., Nouman, M., Srewaradachpisal, S., Movrin, D. (2025). Infill Pattern and Density of 3D-Printed Insoles Alter Energy and Pressure Distribution in Gait. *Applied Sciences*, 15(7), 3916. https://doi.org/10.3390/app15073916

[15] Daryabor, A., Kobayashi, T., Saeedi, H., Lyons, S.M., Maeda, N., Naimi, S.S. (2023). Effect of 3D printed insoles for people with flatfeet: A systematic review. *Assistive Technology*, 35(2), 169–179. https://doi.org/10.1080/10400435.2022.2105438

[16] *https://rysilicone.com/silicone-shore-hardness/*, accessed on28.10.2025.