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SoleMate: The Design and Development of a Smart Insole System

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ABSTRACT

The SoleMate smart insole system, introduced in this study, addresses the growing prevalence of foot disorders and their associated complications. Foot disorders affect a substantial portion of the population, leading to foot pain and gait abnormalities. This research presents a low-cost, innovative solution that combines force-sensitive resistors (FSR), vibration motors, and a gyroscope sensor integrated with an ESP32 microcontroller. This system offers continuous monitoring of foot alignment and plantar pressure, along with the ability to provide alerts for abnormal foot alignment. By utilizing the Internet of Things (IoT) technology through the Blynk app, users can remotely monitor and control the device, enhancing its usability and potential for early detection and intervention in foot-related issues. While the SoleMate system shows promise, there is room for improvement, including reducing the system's size, adding sensors to enhance data collection, and improving the user interface. With its potential to improve foot health and overall well-being, the SoleMate system holds promise for healthcare professionals and individuals seeking effective foot-related problem management and prevention.

INTRODUCTION

The feet are a critical component of the human musculoskeletal system, responsible for supporting the body's weight, aiding in locomotion and playing a vital role in preserving movement control, postural stability, independence and overall well-being (López-López et al., 2021). Currently, there is a rise in the incidence of foot disorders, with rates ranging from 61% to 79% (López-López et al., 2021), indicating pervasive issues that affect a significant portion of the population, causing foot pain and gait abnormalities. Untreated foot pain may result in various complications, including, posture-related problems, reduced walking speed, uneven feet plantar distribution, reduced quality of life (Rodríguez-Sanz et al., 2018) and in the long-term, it could lead to impaired balance, which increases fall risks (Gates et al., 2019).

Furthermore, studies indicate that abnormal foot posture is closely associated with foot pain, lower limb dysfunctions, and low back pain (Menz et al., 2013; Yang et al., 2022). A normal foot posture provides limb stability, while an abnormal one can induce abnormal femur and tibia postures, leg length differences, and may result in a forward tilt of the pelvis and irregular positioning of the lower back vertebrae (Yang et al., 2022). Among the various foot posture abnormalities, in-toeing and out-toeing stand out as some of the most common conditions (Nourai et al., 2015), especially in obese-individuals (Browning, 2012). Left untreated, these conditions can cause lower extremity deformities such as variation in angle of hip and knee adduction (Cui et al., 2019). Toe-walking is another frequency observed condition, primarily affecting children (A. Caserta et al., 2022), but also occurring in adults (Dietz & Khunsree, 2012). Untreated toe-walking increases the chance of losing

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balance and can also lead to social discomfort due to its impact on aesthetic appearance (A. J. Caserta et al., 2019).

Conservative treatments can be used to treat foot conditions, such as postural exercises, muscle stretching, footwear and foot orthoses (A. J. Caserta et al., 2019; Nourai et al., 2015). Vibration applied at the foot can enhance locomotion and mitigate tripping risks (Pathak et al., 2022; Postema et al., 2009). Moreover, in recent years, a wide range of electronics and sensors are being utilized for the creation of wearable devices to help with health management, prevention and diagnosis (Khandakar et al., 2022). According to Gómez-Espinosa et al. (2018), Inertial measurement units (IMU), which integrate a 3-axis accelerometer and a 3-axis gyroscope can be used to develop portable rehabilitation devices. A single IMU can effectively assist in evaluating foot posture, recognizing motion patterns, diagnosing different foot conditions, and enhancing gait for individuals with walking disabilities (Gómez-Espinosa et al., 2018). Moreover, several commercially available sensors can be used to measure foot plantar pressure (Khandakar et al., 2022), which provides valuable insights regarding foot posture and gait analysis.

The internet of Things (IoT) wearables play a significant role in in the healthcare sector (Rejeb et al., 2023). They offer the advantage of enabling remote health monitoring, enhancing healthcare service quality, and reducing costs by providing real-time health data to clinicians and patients for early detection and treatment of health issues, thus improving patient care and resource allocation in the healthcare field (Rejeb et al., 2023).

Within all the aspects mentioned above, a low-cost smart insole system was developed called SoleMate for continuous measurement of foot alignment and plantar pressure. To aid in foot pain and tension relief, the device incorporates vibrators that mimic the effects of a massage. In addition, a graphical user interface (GUI) was designed using IOT app to control the system, display information and alert the user in case of any abnormalities

MATERIALS AND METHOD

In this section, the essential elements of designing the smart insole system will be discussed, emphasizing a hardware-first approach. This approach was used due to the lack of suitable simulation software for the components involved and its adoption in related studies (Lin et al., 2016; Manupibul et al., 2014; Xu et al., 2012).

Figure 1 shows the system architecture of the smart insole system, which consists of the hardware components integrated into the foot insole, microcontroller, connectivity options and the IOT platform used. Embedded within the insole are FSRs, a gyroscope, and vibration motors. The ESP32 gathers data from the sensors and controls the vibration motors, ensuring efficient and accurate operation. The IoT cloud platform connects the ESP32 microcontroller with the Blynk app, enabling data storage, processing, and remote access. For connectivity, the system supports both Bluetooth and Wi-Fi, offering flexible and reliable communication between the device and the mobile app.

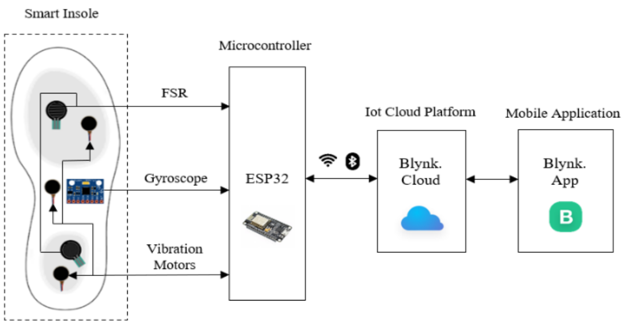

Fig. 1 System architecture of the smart insole system comprising the smart Insole, microcontroller, IoT cloud

Hardware Design

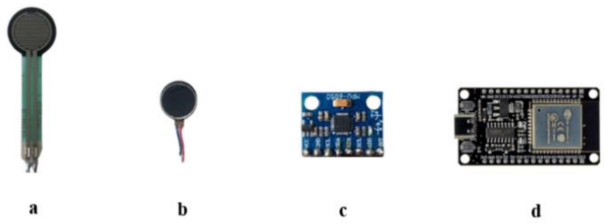

Fig. 2 Hardware components: a) FSR, b) Vibration motor, c) Gyroscope sensor, d) Microcontroller

Two round force sensitive resistors (FSR 402) are used to measure the foot plantar pressure. FSR works by changing its resistance in response to applied force or pressure (Sadun et al., 2016). The resistance of the FSR decreases from 1 MΩ to 10 KΩ as the applied force increases from approximately 0.1kg to 10kg [20]. Each FSR sensor require a voltage divider circuit, which can be set using the following equation:

$$V_O = \frac{V_{cc} \times R_M}{R_M + R_{FSR}} \quad (1)$$

Were, V_O is the output voltage, V_{cc} is the supply voltage, R_M is the measuring resistor (pull-down), and R_{FSR} is the FSR sensor resistance.

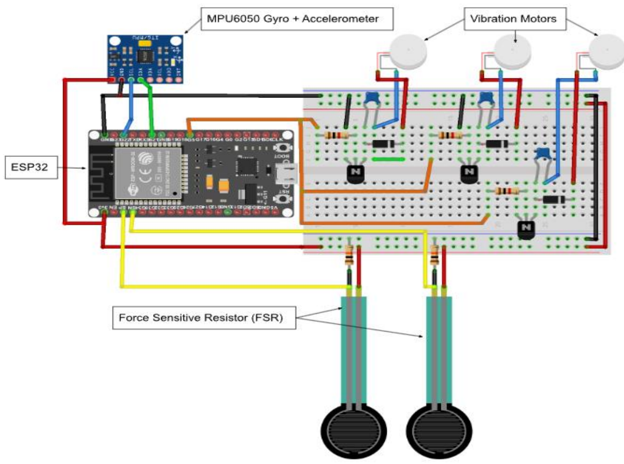

Fig. 3 Complete circuit schematic using fritzing

To create enough vibration at the sole of the feet, three 12mm mini disc vibrating motors are used. Each motor is connected to a reverse biased diode, capacitor and NPN transistor as shown in Figure 3. The diode protects the components against voltage spikes produced by the motor when rotating while the capacitor absorbs the voltage spikes. The transistor is used to amplify the weak current output from the microcontroller needed to drive the vibrating motors.

In addition, a 3-axis gyroscope sensor (MPU6050) is used to measure the rotation of the basic ankle-foot movements used in rehabilitation: yaw (abduction & adduction), roll (plantar flexion & dorsiflexion) and pitch (inversion & eversion) angles (Gómez-Espinosa et al., 2018), as shown in Figure 4.

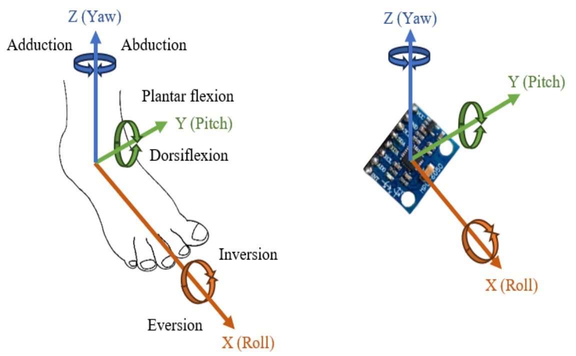

Fig 4 Ankle-foot movements using MPU6050.

All the components are connected to the ESP32 microcontroller as shown in Figure 3. Among the various ESP32 versions developed by Espressif systems company, ESP32-WROOM was chosen, which offers a low-cost solution, Wi-Fi and dual Bluetooth v4.2, communications, and a variety of peripherals (Babiuch et al., 2019).To prevent the deformation of the components, a solid surface must be added to the insole. Therefore, a triple-layer foam is employed as shown in Figure 5, with each layer measuring approximately 3 mm in thickness. This not only ensures the safety of the electrical components, but also offers increased comfort and support to the user. Moreover, Figure 5 below shows the placement of the components in the middle layer, as well as the enclosure box for the circuit and battery which was designed and developed using 3D-printing.

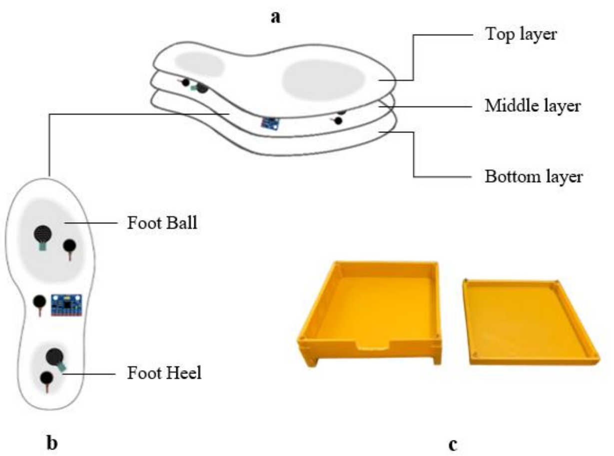

Fig. 5 (a) Triple-layer insole, (b) Sensor placement in the middle layer, (c) 3D printed box.

Software Design

As shown in Figure 1, data exchange between the ESP32 and the components is established via Blynk cloud. Blynk is an internet of things (IoT) platform that allows users to monitor and control electronic devices remotely using Wi-Fi or Bluetooth communication protocols (Durani et al., 2018). In addition, customized mobile application interface compatible with both iOS and android operating systems was created using Blynk app, providing a user-friendly interface for system control and data display. Moreover, to program the ESP32 with the Blynk app, Arduino IDE was used.

Figure 6 Shows the flowchart of the system. The system incorporates three key functions that are controlled and displayed in the Blynk app: vibrating foot massage, Foot plantar pressure and alignment information. The vibration function can be controlled using a simple ON or OFF button in the Blynk app. The analog values from the two FSR sensors were mapped from 0 to 100, and then categorized into three levels: Low (0-33.3), Mid (33.3-66.6) and High (66.6-100).

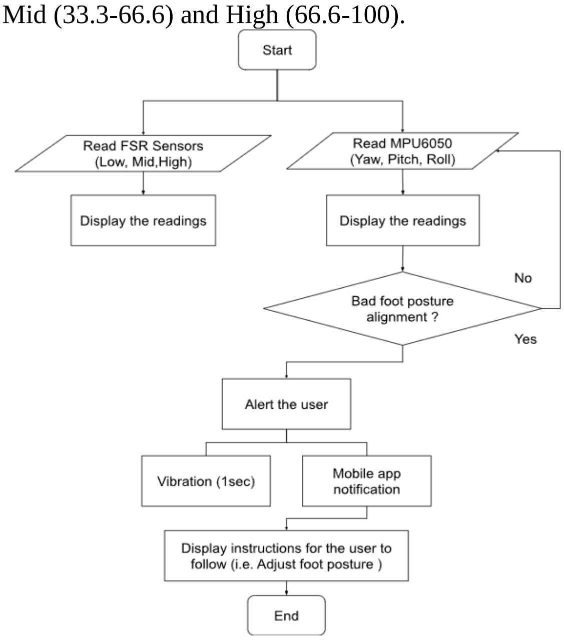

Fig. 6 Flowchart of the system

The Yaw, Pitch, and Roll readings from the gyroscope when the foot is in its normal position (toes facing straight ahead) all read as 0 degrees. From there, a threshold can be established for each motion shown in Figure 4. Whenever these thresholds are exceeded, a notification will be promptly sent through the Blynk mobile app with a one-second vibration at the foot insole to alert the user to adjust his/her foot. This feature can be customized according to the user's specific condition and needs. Further details will be discussed in the following section.

RESULT AND DISCUSSION

In this section, the outcomes of both the hardware and software of the smart insole system are presented. The results highlight the successful integration and functionality of the device. The hardware results focus on the assembly and physical configuration of the smart insole, while the software results emphasize the user interface and data outputs generated by the system.

Hardware Results

The device setup, comprising the components embedded into the middle insole and the 3D-box containing the PCB circuit is as shown in Figure 7.

Fig. 7 (a) Front and back view of the middle layer, (b) 3D printed box and PCB circuit board

The bottom and top layer insoles were attached to the middle layer using double-sided adhesive tape to facilitate easy removal if any adjustments are needed. During the assembly process, all the components were tested to ensure that they were functioning as intended. Figure 8 shows the complete smart insole prototype placed on human leg. An elastic fabric band with Velcro sides is used to hold and attach the 3D-box around the leg.

Fig. 8 (a) Complete smart insole prototype, (b) Device placed on human leg

Fig. 9 GUI of the system in the Blynk app.

Software Results

The graphical user interface of the system as shown in Figure 9, consists of 3 main parts: Firstly, the pressure readings and corresponding levels measured by the FSR sensors located at the heel and ball of the foot. Secondly, the Roll, Yaw, and Pitch angles, which are derived from the MPU6050 gyroscope sensor. Finally, a virtual button that allows users to toggle the vibration function on and off as per their preference.

Figure 10 shows the output for each part of the system when the device is operating. However, there was a large fluctuation in the gyroscope readings when the sensor and vibration motors were working simultaneously. This is due to the mechanical noise generated by the vibration motors. Therefore, a simple solution was to program the gyroscope to only work when the vibration is turned off. This particular issue had no effect on the FSR readings.

Fig. 10 Data displayed from the FSR and gyroscope sensors, and vibration mode on

The FSR readings can be used to describe the plantar pressure of the feet during the gait cycle as shown in Figure 11. The gait cycle stages are divided into 3 phases, foot strike, swing phase and opposite foot strike. During the initial foot strike, there is a high-pressure level at the heel and no pressure at the ball of the foot. As the left swing phase begins, the right foot should be flat to provide single support, with pressure levels being high at both the heel and the ball of the foot. Subsequently, pressure gradually diminishes from the heel and ball until the toes lift off the ground, at which point there should be no detectable pressure at all.

Measuring foot plantar pressure is important for assessing and diagnosing various foot conditions, optimizing footwear and orthotic design (Abdul Razak et al., 2012). For example, adult toe-walkers often exhibit a distinctive gait characterized by a "bouncing" or "mincing" stride, with reduced heel contact when walking (Dietz & Khunsree, 2012). Therefore, with the information that can be obtained from the device, healthcare professionals and researchers can gain valuable insights into the gait patterns and pressure distribution of such conditions, leading to more effective interventions and treatment strategies.

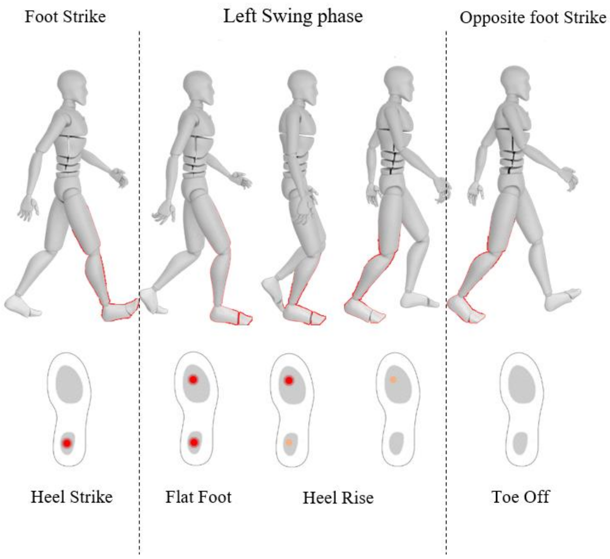

Figure 11. Data displayed from the FSR and gyroscope sensors, and vibration mode on

A simple experiment was conducted to verify the functionality of the MPU6050 with the alert system, in which, all the basic ankle-foot movements mentioned in the previous section were exercised. For the sake of the experiment, the threshold was set as follows: Roll (30°, -20°), Yaw (20°, -20°), Pitch (30°, -50°). When the foot was in normal position (Toes pointing straight ahead), all the readings were recorded at approximately 0°, with a margin of error within +-2°. Whenever the threshold was exceeded, a notification was sent through the Blynk app with a sharp tone and a 1-second vibration to alert the user. Figure 12 shows the Blynk app notification when the yaw value exceeded 20°.

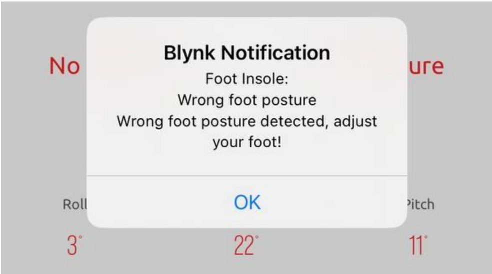

Figure 12. Blynk app notification alert

Measuring foot rotation can serve as a valuable tool for correcting foot posture and alignment, making it applicable as a rehabilitation aid for both healthcare professionals and non-professionals to identify and alert for various foot posture abnormalities. For instance, yaw measurements can be utilized to alert for in-toeing or out-toeing conditions, prompting the user to make necessary adjustments to their foot posture during walking.

Limitations

While the 'SoleMate' smart insole system shows promise in its current iteration, there are several areas that could be improved to enhance its functionality and usability and can contribute to the overall effectiveness of the 'SoleMate' system:

1. Decreasing the size of the system's enclosure by utilizing a smaller microcontroller and optimizing the PCB design and cable connection to make it more comfortable for users and reduce bulkiness.
2. Adding another FSR sensor to the toes could improve plantar pressure detection during all phases of the gait cycle, providing more comprehensive data for analysis.
3. Insulating the MPU6050 sensor with anti-vibration materials to enable it to work simultaneously with the vibration motors.
4. Enhancing the user interface with features like graphical representations and pressure maps.
5. The implementation of advanced algorithms for foot posture analysis would further increase the system's diagnostic capabilities and potentially enable more tailored interventions for users with specific foot conditions.

CONCLUSION

In conclusion, the development of the 'SoleMate' smart insole system represents a promising step towards addressing the rising incidence of foot disorders and associated complications. By integrating electronic components like force-sensitive resistors, vibration motors, and a gyroscope sensor with an ESP32 microcontroller, and coupling it with a user-friendly interface through the Blynk app, this system offers continuous monitoring of foot alignment, plantar pressure, and alerts for abnormal foot alignment. The ability to remotely monitor and control the device via IoT technology enhances its usability and potential for early detection and intervention in foot-related issues. With its low-cost design and potential to improve foot health and overall well-being, the 'SoleMate' system holds promise for both healthcare professionals and individuals seeking to manage and prevent foot-related problems.

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