DESIGN OF INSTRUMENTED INSOLE FOR GAIT DYNAMICS MONITORING

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Abstract

This article focuses on the design and implementation of a device aimed at monitoring gait dynamics. In clinical settings, gait dynamics are conventionally observed within specialized motion laboratories that rely on camera systems or pressure-sensitive floor mats. Unfortunately, these methods provide clinicians with only a temporally restricted perspective on a patient's health within the hospital environment. The objective of this study is to propose and develop a functional prototype of a measurement device that utilizes force-sensing resistors integrated into a sensorics insole placed within a shoe. By fusion of the 3D printing technology and force-sensing sensors, we developed a wearable prototype consisting of an instrumented insole and wireless data acquisition unit. This approach enables the capture of both static and dynamic parameters of gait, not only in clinical environments but also in non-hospital settings.

Keywords

Instrumented insole, force sensitive resistors, gait, plantar pressure, 3D printing

Introduction

Gait, or locomotion, is a common part of everyday life and represents the most natural form of movement for a healthy individual. It is understandable that walking disorders can significantly impact the quality of life and contribute to a loss of personal freedom. Proper interpretation of walking can serve as a sensitive indicator of overall health. However, walking disorders and associated serious neurological or musculoskeletal conditions are currently underdiagnosed [1]. Gait is a basic physiological manifestation of the human body that involves motor activity. Research on human walking includes qualitative and quantitative assessment of its individual phases and the analysis of their static and dynamic parameters [2]. From a clinical perspective, the importance of gait analysis is linked to the increased prevalence of walking disorders in an expanding portion of the population. Walking disorders are primarily caused by neurodegenerative diseases (amyotrophic lateral sclerosis, Parkinson's disease, myelopathy, myopathy), post-traumatic conditions of the lower limbs, improperly learned movement patterns, or simply physiological aging [2–4]. By studying the dynamic parameters of walking, it is possible to detect early signs of the development of certain neurological diseases characterized by poor balance and slower pace of walking. For instance, multiple sclerosis is characterized by a shorter step length, lower walking speed, and higher cadence compared to the healthy population [5].

In a clinical setting, gait dynamics are monitored in specialized motion laboratories based on camera systems or pressure-sensitive floor mats. Parameters observed include step length, walking speed, smoothness of walking, cadence, step angle, ground reaction forces, plantar pressure forces of the foot, duration of toe-off and heel strike, and more [6, 7]. However, such relatively short-term assessments provide doctors with a limited view of the patient's health, and only within the hospital environment under strictly controlled conditions. Another drawback of these systems is the economic aspect concerning the financial costs of equipment and the expertise required from the operating personnel. Beyond the clinical importance of gait monitoring, there is also a significance in monitoring the movement activities of the healthy population, particularly as a preventive measure against lifestyle-related diseases such as obesity and cardiovascular conditions.

In today's era, the monitoring of physical activities is becoming increasingly popular through various forms of wearable electronics, such as smartphones or smartwatches. The fundamental sensory element in the measuring chain is typically an accelerometer (primarily for calculating the dominant harmonic frequency and estimating the number of steps) or a GPS radio communication module (providing additional information for a more precise estimation of the number

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of steps and distance covered). Although these technologies are relatively financially accessible to a broad segment of the population, their output in terms of captured dynamic gait parameters is considerably limited from a clinical perspective.

The aim of this paper is to introduce an innovative design and manufacturing approach for a wearable device capable of capturing the plantar pressure and vertical ground reaction forces using piezoresistive force-sensing resistor (FSR) sensors.

Material and Methods

The device concept comprises an instrumented insole embedded with piezoresistive FSR sensors and a data acquisition unit for wirelessly transmitting the captured data to a client application. Fig. 1 illustrates the block diagram of the device concept.

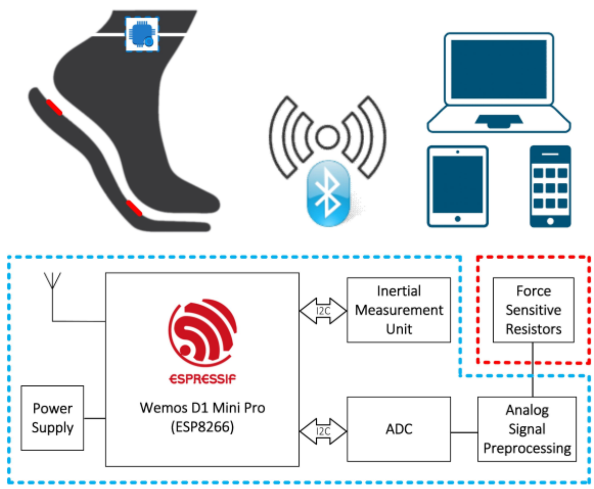

Fig. 1: The block diagram of the device concept.

Force-Sensing Resistor Sensors

The sensory element of the device consists of circular-shaped FSR sensors, specifically the FSR07 model (Ohmite Manufacturing Company, USA) [8]. An FSR sensor is a piezoresistive passive electrical component that enables the measurement of static and dynamic forces applied to its active area. Essentially, it is a flexible multilayered polymer structure with an applied electrically conductive material based on carbon and silver. When mechanically unloaded, the FSR sensor has a relatively high electrical resistance, typically in the order of MΩ, which decreases to values in the order of kΩ with increasing mechanical force applied to its active area (see Fig. 2).

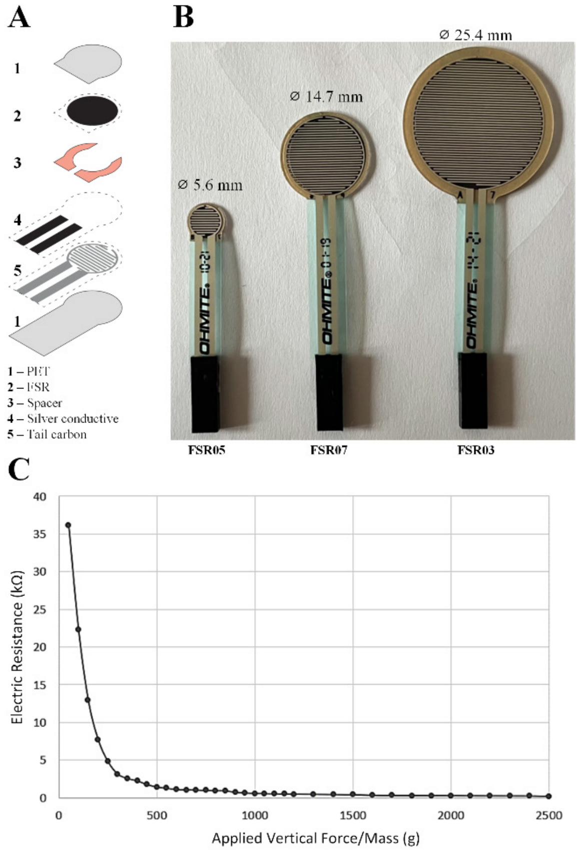

Fig. 2: A—Composition and structure of the FSR sensor; B—Real design of three different FSR sensors; C—Functional dependence of the electrical resistance of the FSR07 sensor on the applied static load [8].

Instrumented Insole

The instrumented insole for shoes serves as a platform for integrating FSR sensors into the user's footwear. Virtual model of the two-layered shoe insole was created using the 3D CAD software (Inventor Professional 2024, Autodesk, USA) (Fig. 3).

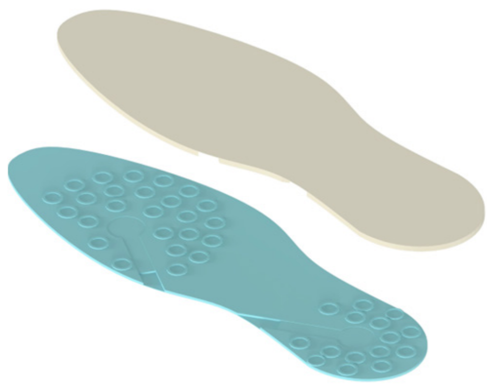

Fig. 3: Virtual model of the two-layered shoe insole.

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It is a custom-made two-layered structure with a height of 3.2 mm produced through 3D printing technology, utilizing the flexible thermoplastic polyurethane (TPU) material (Fig. 4). TPU mechanical properties, particularly strength and flexibility, are similar to those of silicone, significantly enhancing the user comfort of such an insole.

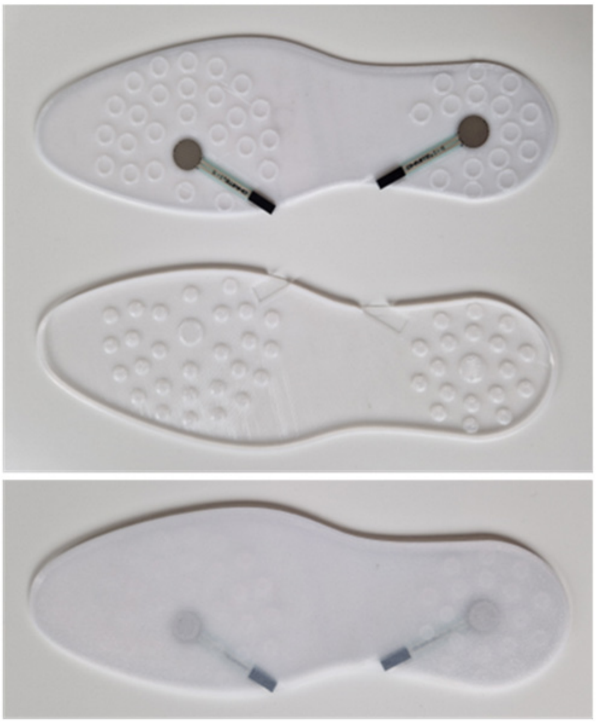

Fig. 4: Real design of the upper and lower insole part; and the final design of the instrumented insole utilizing 3D printing technology and TPU filament.

In the current implementation, a total of two FSR sensors are used, strategically placed to optimize the distribution of plantar pressure during the walking cycle. These sensors are positioned on the front and rear contact surfaces of the foot, where the highest values of plantar pressure occur [9]. Due to the measurement range limitation of the used FSR sensors (up to 5 kg), the design of the insole was expanded with a significant number of spacer pads. These spacers ensure that static or dynamic force during walking is not concentrated solely on the active areas of the FSR sensors.

Data Acquisition Unit

The core of the data acquisition unit represents the ESP8266 microcontroller (Espressif Systems, China) in the form of the Wemos D1 mini Pro development module. This module was chosen for its low power consumption, compact design, and integrated Wi-Fi radiofrequency module [10]. The data acquisition unit is powered by a lithium-polymer battery.

In order to convert the change in the electrical conductivity of the FSR sensor into an electrical voltage, we designed an electrical circuit whose key elements are a voltage divider with a reference electrical resistance and an operational amplifier. The configuration of the connection for analog signal preprocessing of the FSR sensor is depicted in Fig. 5, where the variable electrical resistance of the FSR sensor is denoted as R_{FSR}, the reference electrical resistance is denoted as R_{ref}, V_{CC} represents the 3.3 VDC power supply, *GND* signifies the ground connection, and V_{OUT} is the output signal in the form of measurable electrical voltage. In this configuration, the output electrical voltage increases with increasing force due to the decrease in the internal electrical resistance of the FSR sensor.

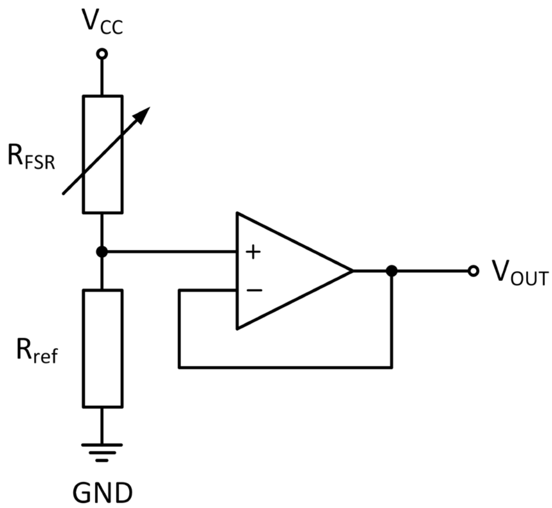

Fig. 5: Electric circuit for analog signal preprocessing from FSR sensor.

Impedance separation of the sensor part (FSR sensors) from the measurement part (analog-to-digital converter) in the circuit configuration requires the use of an operational amplifier. We used the MCP6002 general purpose operational amplifier (Microchip Technology, USA) in a voltage follower configuration, where the inverting feedback is connected to the output. This means that the operational amplifier allows the input signal to pass through without amplification, or with unity gain. It features a high input electrical impedance, ensuring that the elements do not load the signal source even with a significant output power. The output of the voltage divider is described by equation:

$$V_{OUT} = \frac{R_{ref} \cdot V_{CC}}{R_{ref} + R_{FSR}}. \quad (1)$$

The output voltage is digitized through a 16-bit analog-to-digital converter ADS1115 (Texas Instruments, USA). The selected AD converter offers higher resolution compared to the built-in AD converter in the Wemos module. It features adjustable gain through a programmable gain amplifier, a built-in voltage reference and an oscillator. The ADS1115

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performs signal conversion at a speed of up to 860 samples per second and is connected to ESP8266 microcontroller via 2-wire digital interface.

The created firmware for the ESP8266 microcontroller ensures the hosting of a predefined Wi-Fi network and embedded server application which captures the outputs of FSR sensors and reports them wirelessly to the client application running on a personal computer. The data transfer rate can be set programmatically up to 100 Hz. A client application, designed for device control, display and export of measured data has been developed in the MATLAB programming environment (version R2023b, MathWorks, USA).

The functionality of the device prototype and the client application was tested in two scenarios. In the first scenario, the static test aimed to determine the reliability and stability of the received digital data under a constant load for a specified period. The constant load was simulated with calibration weights of 500 g and 1000 g, which were sequentially placed on the active parts of the FSR sensors embedded in the instrumented insole. The second scenario aimed to test the functionality of the device prototype during cyclic weight transfer between the rear and frontal foot parts during walking while wearing an instrumented insole in a sandal. The subject was asked to take precisely ten steps during a 30-second measurement period.

Results

The created prototype of the device for monitoring walking dynamics and the concept of the measuring chain are illustrated in the following figure (Fig. 6).

Fig. 6: The prototype of the created device embedded into a sandal.

The device consists of an instrumented insole integrated with FSR sensors and data acquisition unit, which wirelessly transmits the captured pressure values via a Wi-Fi interface to the client application.

The functionality of the device prototype and the client application was tested through a series of tests. The static test aims to determine the reliability and stability of the received data under constant load. The result of static test is depicted in Fig. 7.

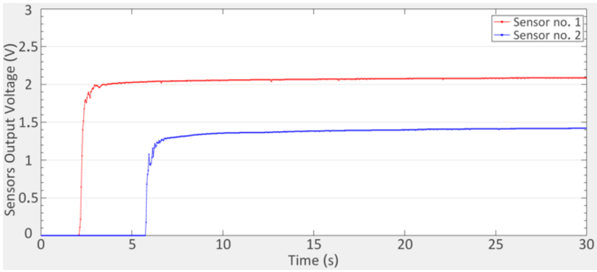

Fig. 7: The static test under constant load (frontal foot part—Sensor no. 1, rear foot part—Sensor no. 2).

Dynamic test reflects the functionality of the device prototype during walking when the subject wears the instrumented insole in sandals. The result of dynamic test is depicted in Fig. 8.

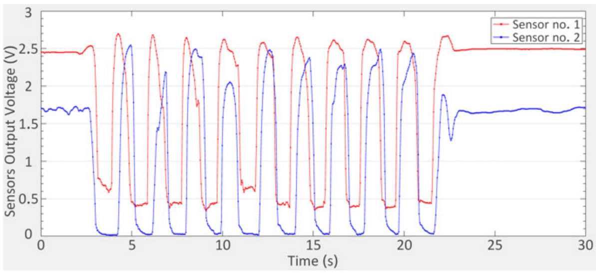

Fig. 8: The dynamic test involved the subject taking precisely ten steps (frontal foot part—Sensor no. 1, rear foot part—Sensor no. 2).

Discussion

This paper presents an innovative approach to the design and manufacturing of a wearable prototype to measure gait dynamics. Two FSR sensors in total are employed in the current implementation. The sensed values of the analog voltage output of the FSR sensors, digitized through an analog-to-digital converter, can be mathematically transformed into physical quantities such as mechanical force, weight, or pressure, considering the sensor's active area. However, for this purpose, calibration of each FSR sensor is necessary to determine its precise transfer characteristic, i.e., the electrical resistance of the FSR sensor depending on the applied mechanical force to its active area (Fig. 2C). Without calibration, only a qualitative assessment of static and dynamic forces during walking through a comparative analysis of FSR sensor outputs from the front and rear parts of the foot is possible.

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The functionality of the proposed system was verified in two scenarios: static and dynamic test (Fig. 7 and Fig. 8). The static test revealed good signal quality in terms of short-term sensors output stability when a constant pressure was applied and wireless data transfer reliability with no packet loss. The dynamic test involved the subject taking precisely ten steps. The segments and phases of the gait cycle can be clearly identified, so the signal is suitable for further analysis. The measured data in the form of sensor output voltage could be further processed to calculate selected gait parameters such as walking speed, smoothness of walking, cadence and so on.

The combination of FSR sensors and 3D printing technology allows us to design low-cost instrumented insole which is much less expensive than equipment required to support the commercial insoles (Tekscan, USA or Novel, Germany). However, they feature more single-point force sensors; thus, denser spatial resolution of plantar pressure distribution.

Conclusion

The objective of this contribution was to develop and fabricate a wearable prototype device that incorporates flexible FSR sensors into an instrumented insole for shoes. Based on the conducted experiments, we can conclude that through the combination of FSR sensors and 3D printing technology, it is possible to create a sensing device capable of monitoring static and dynamic gait parameters. The availability of flexible filaments enables the creation of a user-friendly sensor insole that can be personalized to fit the specific user and foot size. By integrating a larger number of FSR sensors into the insole, it becomes possible to capture the spatial distribution of plantar pressure during walking. The use of 3D scanning and 3D printing technology could also facilitate the creation of orthopedic insoles for shoes. These insoles could not only accommodate the unique shape of the foot but also address any foot damage, allowing for the monitoring of its regression during long-term therapy.

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