Wearable device for detecting flat feet and high arches using pressure sensors based on graphite

Dispositivo vestible para detectar pie plano y cavo utilizando sensores de presión a base de grafito

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Keywords

Medical technology; remote sensing; electronic engineering; biomedical research; device; plantar conditions; Android application.

Abstract

The present study focuses on the design and construction of an innovative device aimed at identifying plantar foot conditions, such as normal, cavus, and flat feet, through the analysis of biosignals. The device was based on two identification methods: the plantar footprint test and the use of a template equipped with digital and analog sensors made of Velostat paper, a material derived from graphite that allows capturing biosignals with high precision. These biosignals were integrated into an Android application, facilitating the diagnosis and appropriate treatment of plantar conditions. The key component of the device was a sensor created with graphite, which functioned as a piezoelectric sensor to acquire and measure the pressure exerted by the foot. Thanks to the sensor's ability to capture biosignals, it was possible to accurately detect and classify plantar conditions. The device stood out for its low cost and seamless integration with the mobile application, becoming a valuable and accessible tool for the healthcare sector, with the potential to significantly improve the quality of life for patients with foot problems through early detection and timely treatment.

Palabras clave

Tecnología médica; detector; tecnología electrónica; investigación médica; dispositivo; condiciones plantares; aplicación de Android.

Resumen

El presente estudio se centra en el diseño y construcción de un dispositivo innovador destinado a la identificación de condiciones plantares del pie, como el pie normal, cavo y plano, mediante el análisis de bioseñales. El dispositivo se basó en dos métodos de identificación: la prueba de la huella plantar y el uso de una plantilla equipada con sensores digitales y analógicos fabricados con papel Velostat, un material derivado del grafito que permite capturar bioseñales con alta precisión. Estas bioseñales se integraron en una aplicación de Android, lo que facilita el diagnóstico y tratamiento adecuado de las condiciones plantares. El componente clave del dispositivo fue un sensor creado con grafito, que operó como un sensor piezoeléctrico para adquirir y medir la presión ejercida por el pie. Gracias a la capacidad de este sensor para captar bioseñales, fue posible detectar y clasificar con precisión las condiciones plantares. El dispositivo se destacó por su bajo costo y su perfecta integración con la aplicación móvil, convirtiéndose en una herramienta valiosa y accesible para el sector de la salud, con el potencial de mejorar significativamente la calidad de vida de los pacientes con problemas en los pies mediante la detección temprana y el tratamiento oportuno.

Introduction

This project focuses on the development of an insole for the detection of various plantar foot conditions, such as normal foot, four degrees of flat foot and three degrees of pes cavus. In addition, temperature measurements are taken to determine whether the person being tested is suffering from diabetes, using temperature sensors built into the insole. If the person is diabetic, a temperature difference of 2.2°C at the same point between the two feet will be observed, which could also indicate the possibility of ulcers. A difference of 2.2°C at the same point on both feet, for a given individual, suggests the appearance of characteristic diabetic foot lesions, such as ulcers or Charcot arthropathy. Scientific studies support the idea that foot temperature control reduces the incidence of ulcers in Diabetes Mellitus [1]. It should be noted that the insole has a relevant feature: a body mass limit of 75 kilograms (kg). Posture, in general, depends on several factors, including the presence of normal arches in the foot, vertical alignment of the ankles and a balanced distribution of body mass around the center of gravity. The foot, as a specialized structure, allows for proper distribution of static and dynamic loads [2].

The main objective of this project is to obtain a portable and low-cost solution for the detection of these conditions, since it has been found that the podoscopes available on the market are expensive and their accessibility is difficult for those who need them. Although there are podoscopes with excellent performance, their price is excessively high, which is why numerous investigations have been carried out to design and manufacture affordable podoscopes that offer reliable results [3]

Materials and methods

Materials

The materials used in this project are as follows:

- Small protoboard
- 2 resistors of 220 Ω
- Insulating tape
- 5 large jumpers of different colors
- 5 large red jumpers
- 5 female-female or male-female jumpers
- DHT11 temperature sensor
- Esp32
- Velostat
- Double-sided tape
- 3 push-button modules
- Mat
- Size 38 of shoe insole
- Flex foam

Methods

The method used in this study is known as the "Plantar Footprint Method". This approach involves assessing the shape and functionality of the foot, diagnosing foot-related problems, and determining the need for custom orthotics and footwear. However, due to its high cost, not all clinics have the necessary equipment, which can lead to medical malpractice [4].

Research on plantar conditions

A normal foot has a specific ratio of A-A' to B-B' measurements in a footprint, but flat and cavus feet have abnormal ratios. However, slight variations may not be pathological [5].

Flatfoot is an inherited condition that affects the inner arch of the foot. In children under three years old, it can be easily detected through an examination using a podoscope. The flatfoot footprint has a flat inner curve [6].

Hollow or high-arched feet have a A normal foot is characterized by a specific relationship between the A-A' and B-B' measurements in a plantar footprint, whereas flat and cavus feet show abnormal relationships. However, it is important to note that slight variations may not necessarily be pathological [5].

Flatfoot is an inherited condition that affects the internal arch of the foot. In children under three years of age, this condition can be easily identified by examination using a podoscope. In the plantar footprint of flat feet, a flat inner curve is observed [6].

On the other hand, hollow feet, also known as high-arched feet, are characterized by an abnormally high arch, which can lead to instability in walking and health problems, such as sprains, overloads and muscle dysfunction. It is recommended that children's feet be examined from the age of 3 years to verify their correct development, since hollow feet can lead to the formation of calluses and metatarsalgia [7].

Figure 1. Plantar condition tests

Data to consider

To determine the maximum load that the sensor can withstand, the weight distribution on both legs of the subject and on the five sensors of the device was considered. Let us assume that the person has a weight of 50 kg, which is equivalent to 490 N, considering the acceleration of gravity of 9.8 m/s^2.

Performing the load distribution, an approximate force of 50 N is obtained. The area of the sensor, which corresponds to a circle with a diameter of 2 cm, is calculated using the formula for the area of a circle:

$$A = \pi \times r^2$$

Substituting the values, we obtain:

$$A = \pi \times (0.01m)^2$$
$$A = 3.1416 \times 10^{-4}\ m^2$$

With the area of the device, we can calculate the pascals applied with the weight of 50 N.

$$P = \frac{N}{A}$$
$$P = \frac{50\ N}{3.1416 \times 10^{-4}\ m^2}$$
$$P = 159154.9431\ Pa$$
$$P = 0.15992\ MPa$$

With this result, mechanical simulations were carried out to evaluate the behavior of the sensor. Similarly, the calculation was performed for a force of 100 N.

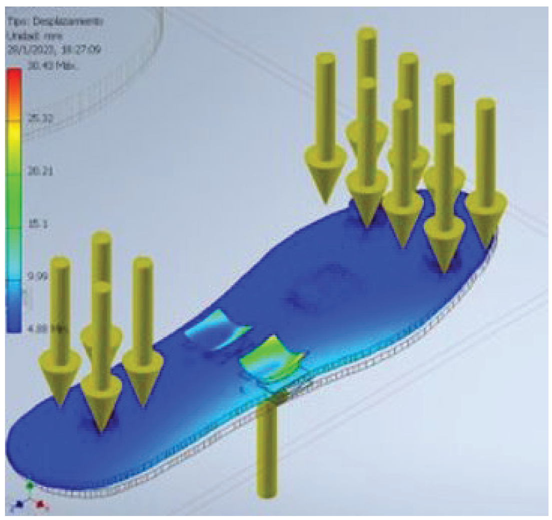

Figure 2. Simulation for 50 N.

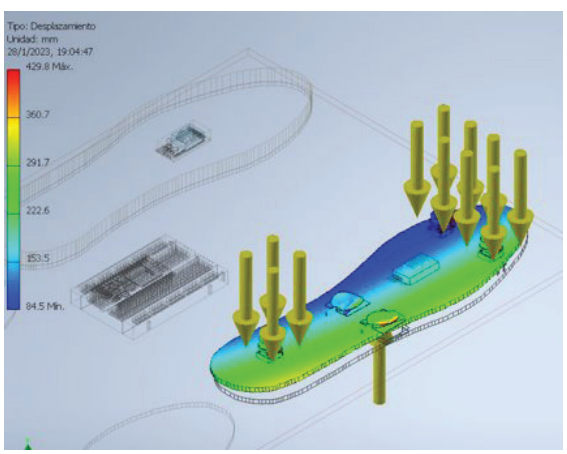

Figure 3. Simulation for 100 N

Results

In the study, Linqstat, a conductive material that has the ability to create flexible sensors by changing its resistance upon application of force, was used. In addition, Velostat, a polymer film with piezoresistive and electrically conductive properties, was used [8].

The combination of these materials allowed the development of pressure sensors with a simple structure consisting of three layers: two conductive wires and an insulator.

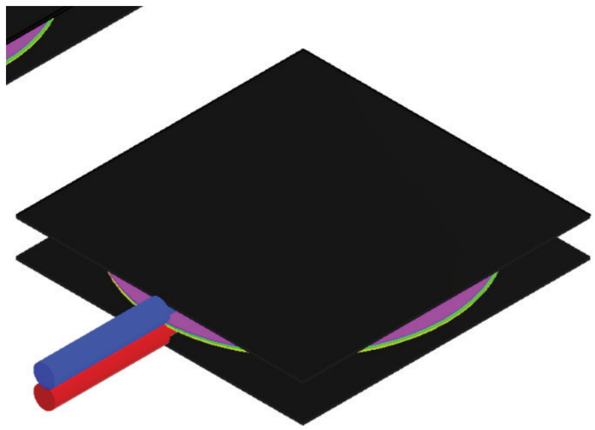

Figure 4. Pressure sensor

To carry out the characterization of the sensor, we proceeded to gradually apply weights on it, taking into account their respective values. The voltage change corresponding to each weight applied was recorded, making the records every 15 seconds to allow the stabilization of the sensor and obtain more accurate results.

Figure 5 shows the calibration curve of the pressure sensor, which was obtained through three tests using the aforementioned methodology and calculating the average of the results obtained. The curve provides information on the relationship between the recorded voltage and the weights applied to the sensor. In addition, the equation of the curve was used to obtain the specific characteristics of the sensor, taking as midpoint the value of 49.26 on the y-axis.

A detailed summary of the characteristics of the manufactured pressure sensor derived from the calibration curve is presented in Table 1. The table provides relevant information on the detectable pressure range, sensor sensitivity and other parameters important for understanding and effectively using the sensor in specific applications.

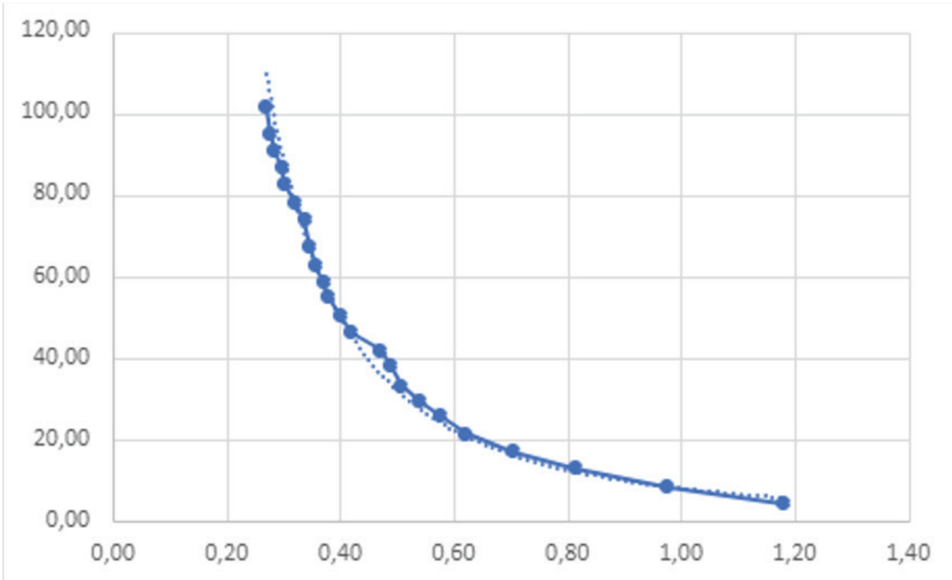

Figure 5. Calibration curve of the pressure sensor.

$$y = 8.0754x^{-1.994} \quad (1)$$

$$49.26 = 8.0754x^{-1.994} \quad (2)$$

$$x = \sqrt[1.994]{\frac{8.0754}{49.26}} \quad (3)$$

$$x = \pm 0.403$$

$$Accuracy\ Error: \frac{100 - 0.403}{100} = 0.995\% \quad (4)$$

$$Repeatability\ Error: \frac{0.18}{101.61} \times 100 = 0.177\% \quad (5)$$

Table 1. Pressure Sensor Features.

Features	Value
Calibration curve	$y = 8.0754x^{-1.994}$
Sensitivity	$8.0755 \frac{N}{V}$
Offset	*2,84 V*
Repeatability Error	0.17%
Accuracy Error	0.995 %

Analysis of the sensor characteristics reveals that participants were able to obtain accurate results about the condition of their feet using the developed system, with an average error of 0.995%. In addition, tests performed to obtain the plantar footprint confirmed the ability of the device to identify the state of the indicated foot.

In the first prototype of the device, as shown in Figures 6 and 7, the electronics were housed in a 3D printed box, while the sensors were strategically placed inside insoles for easy access and use by users.

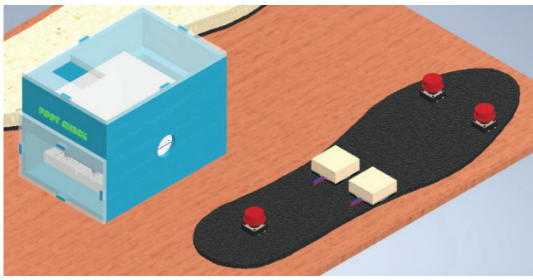

Figure 6. Device modeling.

Fig. 7. First prototype.

The conditions for the sensor were established using pressure percentages adjusted through testing with multiple subjects. These conditions were integrated into the system programming. Figure 8 shows the conditions based on the defined pressure percentages. For the control of the ESP32 microcontroller, Arduino programming was used, which includes the characterization of the sensor equation and all necessary commands.

#Sensor	NORMAL	CAVO I	CAVO II	CAVO III
SP1	1	1	1	1
SP2	1	1	1	1
SP3	40-60	40-60	12-15	7-12
SP4	7	7	7	7
SP5	1	1	1	1
#Sensor	**PLANO I**	**PLANO II**	**PLANO III**	**PLANO IV**
SP1	1	1	1	1
SP2	1	1	1	1
SP3	40-100	40-100	40-100	40-100
SP4	7-16	15-18	19-35	36-100
SP5	1	1	1	1

Figure 8. Condiciones del pie en base a porcentajes de presión.

In order to visualize and obtain real-time data, a user interface was developed (Figure 9). This interface allows user interaction and real-time monitoring of the patient's plantar condition. The application is easy to use and provides essential information, such as company details, different plantar conditions available, and the sensors being monitored.

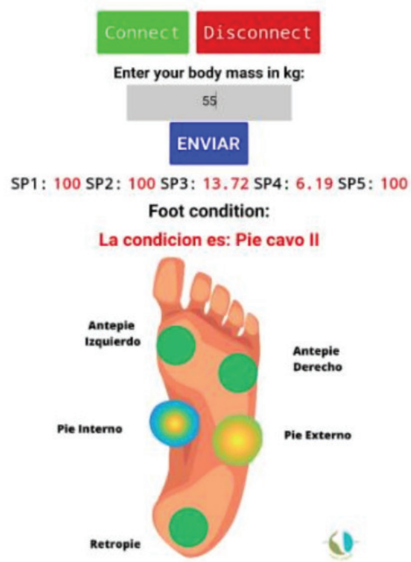

Figure 9. App interface.

The app's interface shows a visual representation of the feet, where three support points are identified by digital sensors in green, and two analog sensors that indicate different levels of plantar involvement. These sensors light up in proportion to the percentage of pressure applied.

Conclusions

Currently, the "FOOT CHECK" device is designed for real-time monitoring, however, work is underway to improve its structure to allow users to use it for longer periods of time. The main objective is to store the data obtained to facilitate more effective patient follow-up in the future. Since plantar conditions are more susceptible to correction in children, the development team is exploring ways to make the biomedical images interactive in the app, in order to increase patient engagement in the use of the device.

The "FOOT CHECK" device along with its app, offers an affordable and accessible alternative to the podoscope for diagnosing plantar conditions. Although still under development, the device is already functional and connects to the ESP32 server via Bluetooth to determine and monitor plantar conditions. To ensure proper use of the device, manuals have been developed to provide the necessary instructions.

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