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Smart Footprint Mapping: Hall Effect Magnetic Field Pedobarograph

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***Abstract*—The development of a magnetic field pedobarograph based on Hall effect sensors is presented as an innovative technical solution to support orthopedic diagnostics. Traditional footprint analysis relies heavily on visual observation, requiring extensive expertise for accurate assessments. To enhance the diagnostic accuracy and provide quantifiable data, we propose a novel system that detects the plantar pressure distribution through magnetic field variations with high sensitivity. This solution enables precise footprint evaluation, particularly benefiting patients with conditions such as diabetic foot ulcers, where conventional methods face limitations. The proposed device offers a cost-effective, non-invasive alternative, expanding the access to high-precision plantar pressure analysis in both clinical and research environments.**

***Index Terms*—Hall effect sensors, plantar pressure analysis, biomechanics, gait analysis.**

I. Introduction

Plantar pressure analysis is a non-invasive technique used to evaluate the distribution of pressure exerted by the foot on the ground. Although this method has proven effective in identifying key pressure points associated with various pathologies, it often relies on clinical interpretation and expensive instrumentation. To address these limitations, the present work introduces a technically innovative solution: a magnetic field-based pedobarograph designed to improve accuracy, reduce cost, and facilitate early diagnosis of biomechanical abnormalities (Cavanagh & Ulbrecht, 1994; Hughes et al., 1993).

Currently, there are multiple tools available to detect abnormalities in the plantar footprint, with the podoscope and pedobarograph being among the most common and accessible. The classic podoscope, also known as a pedometer, is a simple and versatile clinical diagnostic device that facilitates the visualization and analysis of plantar footprints and the various axes of the foot.

Additionally, it allows for the rapid and comfortable study of the foot in both normal and pathological conditions (D'Agostino et al., 2021). The pedobarograph, on the other hand, is a device that measures plantar pressure, providing accurate data on pressure distribution during walking or in a static position, making it a valuable tool in clinical gait analysis and biomechanical studies (Orlin and McPoil, 2000; Pataky, Goulermas, and Crompton, 2008; Razak et al., 2012).

Advances in sensor technology and data processing have improved the accuracy of plantar pressure measurements. These developments have enhanced the understanding of foot biomechanics, the design of orthotics and footwear, and the treatment of related pathologies (Chen et al., 2010).

One of the most concerning pathologies with a high mortality rate is the so-called "diabetic foot." This condition is often overlooked in routine studies and treatments, and many patients suffering from diabetic foot receive inadequate or delayed care, frequently leading to limb amputation (Armstrong et al., 2017). Although techniques for managing diabetic feet have evolved in recent years, progress remains slow. One of the most promising fields involves the study of magnetic fields and thermodynamics, as both play a role in the condition's progression. A key characteristic of the diabetic foot is reduced blood circulation, leading to poor oxygenation in the limb (Hicks et al., 2016). This impaired circulation results in a significant decrease in foot temperature, which can serve as a predictor of the onset of neuropathic ulceration. Monitoring temperature changes can help reduce the risk of ulceration, making temperature control a valuable tool in diabetic foot management (Lavery et al., 2007; van Netten et al., 2020).

Patients with poor posture can develop malformations that, together with the distribution of the footprints, often due to inadequate training, can be linked to back pain, calf fatigue, and other musculoskeletal issues (Lee and Lee, 2018). This has driven improvements in plantar pressure analysis using high precision pedobarographs, which in turn has increased the cost of these devices. This process of innovation has led to the development of thermal pedobarographs, which are among the most accurate. However, due to their high cost and challenges in characterizing plantar pressure distribution in patients with diabetic foot, two alternatives have emerged: pedobarographs based on resistive sensors and those utilizing magnetic fields (Razak et al., 2012).

Resistive sensors are currently the most well-known and widely used, but they require many sensors to capture a detailed image. Additionally, they often fail to detect the complete shape of the foot because they rely on the contact area to record data (Hsu et al., 2005). Magnetic field pedobarographs, on the other hand, can reduce the number of sensors while detecting small variations in foot structure, making them highly useful for designing corrective insoles (García-González et al., 2019). One of the key advantages of both resistive and magnetic field sensors is their adaptability, allowing for the creation of

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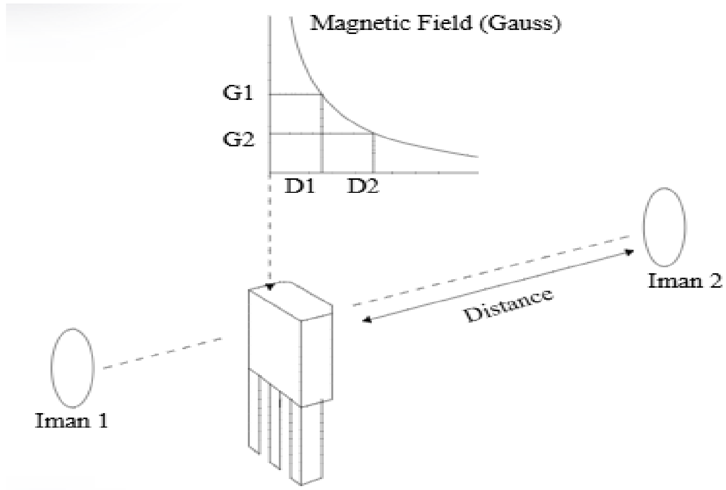

Fig. 1. Unipolar head-on mode.

pressure-sensitive mats that conform to various foot shapes and sizes, thus improving the usability and versatility of pedobarographs

The magnetic field supports blood circulation and bone formation and influences bone density reduction. One of the most promising effects is the Hall effect, which interacts at moderate magnetic field strengths (<T) (Schmidt-Rohlfing et al., 2012). Increased circulation contributes to temperature regulation in the extremities; however, this remains a challenge when conducting traditional measurements in patients with diabetic foot (Tenforde, 2005).

One of the main challenges in the field of plantar pressure analysis is the high cost of diagnostic studies, which can limit the accessibility for many patients. Additionally, certain clinical practices may lead to overtreatment, sometimes to justify these costs, raising ethical concerns (Bus and van Netten, 2016). Reducing costs and expanding the accessibility of these studies would not only enhance diagnostic accuracy but also improve patient outcomes and preventive care (Najafi et al., 2017). The following section presents an example of the benefits of this technology in clinical practice.

This study aims to develop and evaluate a novel plantar pressure measurement system using Hall effect sensors, designed to enhance the accuracy and affordability in footprint analysis. The proposed system consists of pressure-sensitive inserts composed of three key components: a Hall effect sensor, a flexible material layer, and a magnet positioned above the flexible material to generate a magnetic field. By leveraging the deformation of the flexible material under pressure, the system detects small variations in the plantar pressure based on changes in the magnetic field strength. This approach seeks to improve the precision of plantar pressure assessment while offering a cost-effective alternative to existing technologies.

II. Theory

The static magnetic field (SMF) has played a crucial role in technological advancements. Its behavior is well understood, particularly its close relationship with the electric current flow. When an electric current passes through a conductor, it generates a magnetic field perpendicular to the current flow. This phenomenon was first discovered in 1820 by Danish scientist Hans Christian Ørsted, who demonstrated that an electric current could deflect the needle of a magnetized compass, revealing the fundamental link between electricity and magnetism (S. Ellingson, 2018).

Subsequently, in 1831, Michael Faraday and Heinrich Lenz formulated what is now known as Faraday's Law of Induction, which mathematically describes how a changing voltage can induce a magnetic field (Jackson, 2024).

However, it was not until 1879 that the American scientist Edwin Herbert Hall discovered the Hall effect, a key principle in electromagnetism. The Hall effect describes how charged particles moving through a conductor are deflected when exposed to a perpendicular magnetic field, causing a measurable voltage difference across the conductor. This principle is the foundation of the Hall effect sensors, which determine the magnetic field strength based on the voltage variations.

The Hall effect sensors can determine the magnetic field strength based on the voltage variations. Since the strength of a static magnetic field decreases with distance, following an inverse square law, these sensors can accurately measure small variations in distance and pressure, as illustrated in Fig. 1 (MICRO SWITCH).

Hall effect sensors are integrated into pressure-sensitive inserts consisting of three main components:

– A Hall effect sensor, responsible for detecting changes in the magnetic field.
– A flexible material layer that deforms under pressure.
– A magnet, positioned above the flexible layer, generates a constant magnetic field.

When pressure is applied, the flexible material deforms, reducing the distance between the magnet and the Hall effect sensor. This increases the magnetic field strength detected by the sensor. Since the strength of a static magnetic field decreases with distance following an inverse square law, this

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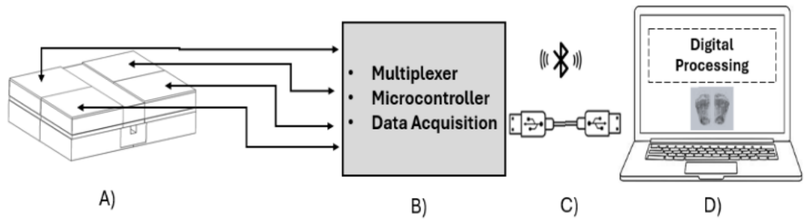

Fig. 2. Stages of the magnetic field pedobarograph operation:
(A) Sensing module and structural framework, (B) Multiplexer and data acquisition system,
(C) Dual communication interface, and (D) Digital analysis and visualization.

configuration enables precise pressure variation measurement (ETC2., 2024; MICRO SWITCH, 2020).

III. Experimental Development

The pedobarograph is composed of Hall effect sensors, which enable the detection of variations in pressure exerted by the plantar footprint. Its structure is divided into four main components, as illustrated in Fig. 2.

A. Sensing module and structure

The operation of the Hall sensor and its configuration with the magnet and flexible material were previously described in Section 2 – Theory. This section details the system assembly.

The system is composed of multiple layers, integrating magnetic fields, and a sensing layer designed to detect variations in both magnetic field strength and pressure. This layered structure enables precise and detailed measurement of plantar pressure distribution.

The sensors are strategically positioned at equal distances to ensure accurate data mapping. The uppermost layer consists of deformable material embedded with magnets, which generate a static magnetic field that interacts with the sensors to effectively measure the applied pressure.

B. Multiplexer/data acquisition

As illustrated in Figure 2(B), the system incorporates a multiplexer integrated with a data acquisition module, responsible for transmitting both analog and digital signals to a microcontroller. The multiplexing system optimizes the management of multiple pressure sensors distributed across the magnetic field pedobarograph platform, ensuring efficient data processing.

The acquisition process captures analog and digital signals, which are subsequently processed by the microcontroller. This central processing unit interprets, organizes, and conditions the data, facilitating accurate analysis and visualization for biomechanical assessment.

C. Dual communication interface

The acquired data is transmitted through a dual communication interface, supporting both wired (USB) and wireless (Bluetooth) connectivity. This flexibility enables seamless data transfer to the analysis and visualization system, allowing real-time monitoring on a mobile device (see Figure 2C)

D. Digital analysis and visualization

The acquired data undergo digital processing using a custom software developed in Python. The software features a graphical user interface (GUI) that facilitates real-time visualization, signal filtering, and calibration of the pressure data.

Additionally, a color mapping algorithm assigns specific hues to different pressure intensities, enabling intuitive analysis of the plantar footprint.

To enhance spatial resolution and visual continuity, an augmented matrix was implemented, and the numerical solution to the Laplace equilibrium equation was employed. This allowed the redistribution of sensor pressure values across neighboring pixels, producing smoother and more accurate pressure maps. These image-processing techniques significantly improved the diagnostic potential of the system. (see Figure 2D).

E. Pedobarograph construction and calibration

The data collected by the pedobarograph undergo digital analysis, enabling a detailed mapping of pressure distribution. This approach enhances spatial resolution by optimizing pixel characterization relative to the number of sensors employed, thereby reducing the required sensor count without compromising accuracy.

The linear Hall effect sensors were characterized based on specifications from their datasheet [11], and neodymium magnets with a disk geometry were selected for integration. Additionally, the magnetic field behavior was analyzed as a function of distance to ensure optimal sensor performance.

The electronic system employs 64 Hall effect sensors (model 49E), multiplexed and connected to an Arduino Nano microcontroller.

The system operates with a sampling frequency of 100 Hz and utilizes the native 10-bit analog-to-digital converter (ADC) of the microcontroller. No additional signal amplification is required, as the Hall sensors provide sufficient sensitivity within the expected pressure range. The entire system is powered by an external 5V source.

The final assembly of the prototype is presented in Fig. 3, demonstrating the versatility of the magnetic field pedobarograph, which can be used both with and without socks, providing comfort and practicality for users during measurement.

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Fig. 3. Final perdobarograph of the magnetic field system with Hall effect sensors.

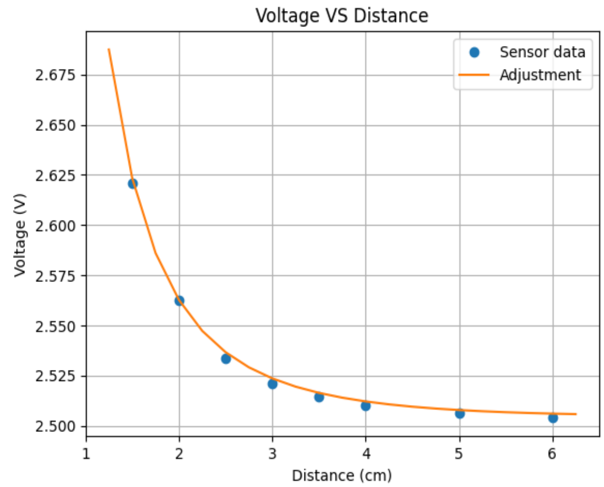

Fig. 4. Characterization of the sensor and the magnetic field exerted by a neodymium magnet with disk geometry.

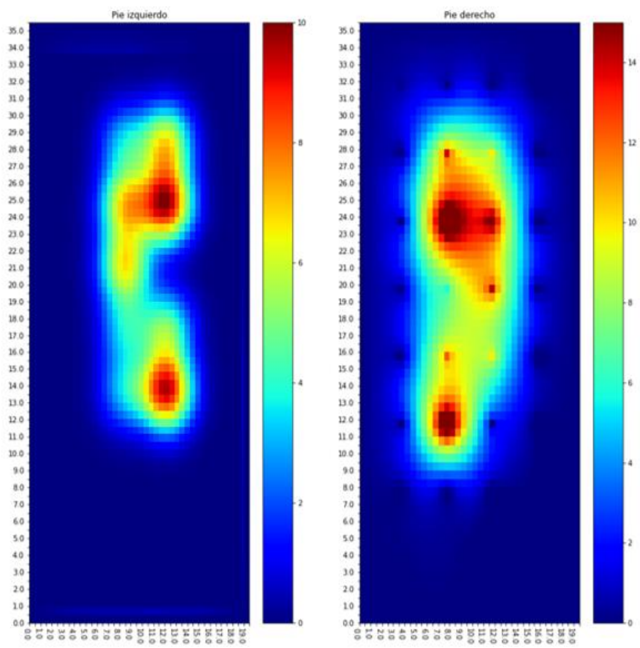

Fig. 5. Image generated by prototype magnetic field Pedobarograph.

IV. Results

The characterization results exhibit an exponential fit, as illustrated in Figure 4. The evaluation involved measuring the sensor response while varying the distance between the sensor and the magnet, revealing exponential behavior.

The statistical analysis yielded a standard deviation of 6.2529 and a variance of 39.0990, with a coefficient of determination ($R^2 = 0.9967$), indicating a high goodness of fit.

The images generated by the magnetic field pedobarograph prototype reveal variations in plantar pressure, enabling a detailed visualization of footprint distribution, as illustrated in Figure 5. Notably, a significant change is observed in the areas of highest pressure, providing valuable insights into load distribution and potential biomechanical imbalances.

V. Discusion

The development of pedobarographs based on magnetic field sensors represents a significant advancement in plantar pressure analysis. Traditional pedobarographs often rely on resistive or capacitive sensors, which, while effective, have limitations in terms of spatial resolution and durability (Giacomozzi, 2010).

In contrast, Hall effect sensors provide high sensitivity to pressure variations while reducing the number of required sensors, improving efficiency and cost-effectiveness (Mickle et al., 2011).

Furthermore, the integration of magnetic field-based sensing aligns with recent trends in biomechanical research, where magnetic and electromagnetic technologies have been explored

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TABLE 1. COMPARATIVE OVERVIEW OF COMMERCIAL *VS.* PROPOSED MAGNETIC FIELD PEDOBAROGRAPH.

Feature	**Commercial Pedobarographs**	**Proposed Magnetic Field Pedobarograph**
Sensor Type	Resistive or capacitive	Hall effect (49E)
Number of Sensors	100–150+	64 (multiplexed)
Pressure Mapping Resolution	High	Medium–High (enhanced by interpolation)
Signal Amplification Needed	Yes	No
Custom Software	Limited / proprietary	Fully customizable (Python)
Real-time Visualization	Available	Available (GUI in Python)
Portability	Low–Medium	High

for both diagnostic and therapeutic purposes (Zhang et al., 2020).

Despite these advantages, further studies are required to validate the clinical accuracy of the device in diverse patient populations. Future work should focus on optimizing sensor calibration, improving real-time data processing, and conducting comparative studies against gold-standard pressure measurement systems.

A comparative summary between traditional commercial pedobarographs and the proposed prototype is presented in Table 1.

While the proposed pedobarograph demonstrates promising results, several limitations must be addressed in future iterations. The current prototype uses a 10-bit ADC, which may limit pressure resolution for certain clinical applications. Additionally, sensor calibration is manually adjusted and could benefit from automated procedures.

At present, the system requires software installation and a direct connection to a computer, which limits portability. Future work will focus on integrating a Raspberry Pi to develop a self-contained, all-in-one solution that enhances usability and mobility. Other improvements include increasing the sensor array density, employing higher-resolution ADCs, and validating the system against commercial gold-standard platforms through clinical testing.

VI. CONCLUSION

The results obtained demonstrate that the proposed prototype meets the expected performance criteria. The analysis of the generated images confirms the feasibility of developing a magnetic field pedobarograph capable of evaluating plantar pressure distribution using Hall effect sensors.

This device offers a precise and non-invasive method for assessing the footprint, with significant potential for clinical applications in orthopedics. Its ability to detect abnormalities in foot biomechanics makes it a valuable diagnostic tool.

Additionally, compared to commercially available pedobarographs, this prototype presents cost-effective advantages while leveraging advances in magnetobiology, both in sensor technology and therapeutic applications.

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